Received: 26 June 2023 | Revised: 13 December 2023 | Accepted: 24 January 2024

DOI: 10.1002/ecm.1603

ECOLOGICAL MONOGRAPHS
ECOLOGICAL SOCIETY OF AMERICA

ARTICLE

Impacts of host availability and temperature on mosquito-borne parasite transmission

Kyle J.-M. Dahlin[1,2] | **Suzanne M. O'Regan**[1,2] | **Barbara A. Han**[3] | **John Paul Schmidt**[1,2] | **John M. Drake**[1,2]

[1]Odum School of Ecology, University of Georgia, Athens, Georgia, USA
[2]Center for the Ecology of Infectious Diseases, University of Georgia, Athens, Georgia, USA
[3]Cary Institute of Ecosystem Studies Box AB, Millbrook, New York, USA

Correspondence
Kyle J.-M. Dahlin
Email: kyledahlin@vt.edu

Present address
Kyle J.-M. Dahlin, Department of Mathematics, Virginia Tech, Blacksburg, Virginia, USA.

Funding information
NSF Ecology and Evolution of Infectious Diseases, Grant/Award Number: DEB 1717282

Handling Editor: Samraat Pawar

Abstract

Global climate change is predicted to cause range shifts in the mosquito species that transmit pathogens to humans and wildlife. Recent modeling studies have sought to improve our understanding of the relationship between temperature and the transmission potential of mosquito-borne pathogens. However, the role of the vertebrate host population, including the importance of host behavioral defenses on mosquito feeding success, remains poorly understood despite ample empirical evidence of its significance to pathogen transmission. Here, we derived thermal performance curves for mosquito and parasite traits and integrated them into two models of vector–host contact to investigate how vertebrate host traits and behaviors affect two key thermal properties of mosquito-borne parasite transmission: the thermal optimum for transmission and the thermal niche of the parasite population. We parameterized these models for five mosquito-borne parasite transmission systems, leading to two main conclusions. First, vertebrate host availability may induce a shift in the thermal optimum of transmission. When the tolerance of the vertebrate host to biting from mosquitoes is limited, the thermal optimum of transmission may be altered by as much as 5°C, a magnitude of applied significance. Second, thresholds for sustained transmission depend nonlinearly on both vertebrate host availability and temperature. At any temperature, sustained transmission is impossible when vertebrate hosts are extremely abundant because the probability of encountering an infected individual is negligible. But when host biting tolerance is limited, sustained transmission will also not occur at low host population densities. Furthermore, our model indicates that biting tolerance should interact with vertebrate host population density to adjust the parasite population thermal niche. Together, these results suggest that vertebrate host traits and behaviors play essential roles in the thermal properties of mosquito-borne parasite transmission. Increasing our understanding of this relationship should lead us to improved predictions about shifting global patterns of mosquito-borne disease.

KEYWORDS
climate change, host availability, malaria, mosquito-borne parasite transmission, mosquito–host contact, thermal tolerance, trait thermal performance curves, trait-based approaches, vector-borne diseases, zoonoses

INTRODUCTION

Global climatic warming is predicted to cause significant shifts in the geographic distributions and abundances of important vectors of pathogens of humans and wildlife, such as malaria (*Plasmodium falciparum*) (Ryan et al., 2020) dengue (DENV), zika (ZIKV), and chikungunya viruses (Ciota & Keyel, 2019; Mordecai et al., 2017; Ryan et al., 2019; Tesla et al., 2018) and West Nile virus (WNV) (Shocket et al., 2020). Additionally, emerging mosquito-borne diseases are an increasing threat to human populations (Jones et al., 2008; Ryan et al., 2019). A more robust understanding of where mosquitoes and their zoonotic pathogens are likely to spread can better prepare policymakers and public health organizations to manage and mitigate the public health burden caused by these zoonoses (Daszak et al., 2000; Laporta et al., 2015; Messina et al., 2016, 2019).

The question of whether and where climate change is most expected to alter mosquito-borne disease risk remains open (Ciota & Keyel, 2019; Franklinos et al., 2019; Ogden, 2017). Several recent theoretical studies have sought to improve our understanding of the relationship between temperature and the transmission potential of mosquito-borne pathogens (Brady et al., 2014; Johnson et al., 2015; Mordecai et al., 2013, 2017, 2019; Ngonghala et al., 2021; Okuneye & Gumel, 2017; Robert et al., 2019; Rohr & Cohen, 2020; Shocket et al., 2020; Tesla et al., 2018; Villena et al., 2020). Throughout, we use the term "parasite" to refer generally to eukaryotes (such as *Plasmodium* malaria), bacteria, and viruses that are transmitted by mosquitoes to a vertebrate host. These studies typically view the basic reproduction number of the system, $\mathcal{R}_0$, as a measure of the thermal performance of the parasite population. $\mathcal{R}_0$ is defined as the average number of new infections produced by a typical infectious individual over the course of their infectious period in a completely susceptible population (Diekmann et al., 1990). A considerable body of work has focused on estimating quantities that describe mosquito and parasite thermal biology, specifically the optimal temperature for transmission and the temperature ranges in which mosquito and parasite populations persist (Ciota & Keyel, 2019; Gething et al., 2011; Mordecai et al., 2013, 2017, 2019; Ngonghala et al., 2021; Ryan et al., 2019; Shocket et al., 2020; Tesla et al., 2018; Villena et al., 2020). Other studies have emphasized the temperature dependence of host and parasite interactions (Cohen et al., 2020; Rohr & Cohen, 2020). Studies indicate that, while some regions may experience decreased risk from mosquito-borne pathogens under future climate scenarios, global mosquito-borne disease transmission is nonetheless predicted to increase, and areas that are currently free of transmission may be invaded (Mordecai et al., 2017; Ryan et al., 2019). Understanding the links between temperature and mosquito-borne pathogen transmission is therefore essential for preparing for regional shifts in the patterns of mosquito-borne disease risk.

Instead of calculating $\mathcal{R}_0$ directly, most theoretical studies have relied on relative transmission measures that ignore traits of the vertebrate host. For instance, vectorial capacity, normalized basic reproduction numbers, and relative basic reproduction numbers obtained from the traditional Ross–Macdonald model are commonly used to quantify the effects of temperature on transmission (Gething et al., 2011; Johnson et al., 2015; Mordecai et al., 2017, 2019; Reiner Jr et al., 2013). These relative transmission measures are used because they require only mosquito and parasite parameters, which can be estimated from data collected in laboratory or field studies (Smith et al., 2012, 2014).

But a useful property of the basic reproduction number is that it is a threshold parameter: When $\mathcal{R}_0$ exceeds one, parasite invasion and the sustained transmission of parasites within a community are predicted to occur (Diekmann et al., 1990; van den Driessche & Watmough, 2002). While relative measures, like vectorial capacity, may express the relative risk of parasite invasion, they do not tell us whether a higher risk of invasion is also predicted to lead to outbreaks (i.e., $\mathcal{R}_0 > 1$). When vertebrate host traits are incorporated into models, $\mathcal{R}_0$ can be calculated directly and retains its utility as an outbreak threshold.

These past studies have also ignored the role of host availability on transmission. In the context of mosquito blood meal seeking, host availability refers to both the abundance of hosts (which overlap geographically and temporally with the mosquito population) and their tolerance to being bitten by mosquitoes (i.e., their willingness or ability to engage in defensive behaviors) (Yan et al., 2021). Epidemiological models of mosquito biting have generally ignored vertebrate host availability, despite ample empirical evidence of its importance to mosquito feeding success (Darbro & Harrington, 2007; Edman et al., 1972; Edman & Kale, 1971; Edman & Scott, 1987; Klowden & Lea, 1979; Walker & Edman, 1986). For example, it is known that vertebrate host defensive behaviors can increase opportunities for transmission by inducing multiple blood feeding in mosquitoes (Davies, 1990; Klowden & Lea, 1979). On the other hand, defensiveness can lead to mortality in mosquitoes, which in turn might reduce transmission (Anderson & Roitberg, 1999; Lyimo et al., 2012). There are several other mechanisms by which vertebrate host defensive behaviors can affect interspecific encounter rates, which we outline in a subsequent section of this paper.

These issues are not merely of academic interest. The empirical evidence that host availability significantly affects the relationship between temperature and parasite transmission is accumulating (Li et al., 2021; Liu et al., 2020; Nguyen et al., 2021; Nova et al., 2021). Using time-series case data from San Juan, Puerto Rico, Nova et al. (2021) found that the size of the susceptible human population altered the relationship between temperature and dengue incidence. Their study showed that when susceptible population density was low, temperature had no effect on dengue incidence, but when susceptible density was high, dengue incidence increased with temperature. In a snail–*Schistosoma*–human transmission system, Nguyen et al. (2021) found that reducing snail populations (either directly or by reducing their carrying capacity) led to an increase in the optimal temperature for transmission of greater than 1°C. More directly related to this study, research into the effect of climate on dengue outbreaks has shown that population density and temperature interact to drive incidence (Liu et al., 2020) and that the combination of these two variables is a stronger driver of incidence than the two variables considered independently (Li et al., 2021).

Because of this empirical evidence for a relationship between host availability and vector-borne parasite transmission, we sought to better understand how host availability could affect two properties of transmission: the transmission thermal optimum T_{opt}, the temperature at which transmission is optimized, and the parasite population thermal niche, the range of temperatures at which parasite transmission is sustained (Huey & Stevenson, 1979; Huxley et al., 2022). To evaluate the role of vertebrate host behavior, we considered two cases: (1) limited and (2) unlimited tolerance to being bitten by mosquitoes. In the first case, vertebrate hosts engage in effective defensive behavior that places an upper bound on the rate at which they are bitten. To model limited biting tolerance, we used the Chitnis dynamic contact rate model (Chitnis et al., 2006; Thongsripong et al., 2021). The second case was modeled using the contact rates from the standard Ross–Macdonald model (Smith et al., 2012). We then parameterized these models for five mosquito-borne parasite systems: *Aedes aegypti*–DENV, *Ae. aegypti*–ZIKV, *Ae. albopictus*–DENV, *Anopheles gambiae*–*Plasmodium falciparum*, and *Culex quinquefasciatus*–WNV. Following previously established methods, we derived thermal performance curves (TPCs) of mosquito and parasite traits from laboratory data to parameterize each of these systems (Johnson et al., 2015). For each system, we calculated the thermal optimum for transmission and parasite population thermal niche across a gradient of vertebrate host availability, varying both the population density and the biting tolerance of the vertebrate host.

Our analysis yielded two main conclusions. First, the thermal optimum of transmission may shift as vertebrate host availability increases. At low vertebrate host population densities, limited biting tolerance led to T_{opt} being altered by as much as 5°C compared to the unlimited biting case. The magnitude and direction (warmer or cooler) of this change depended on the system, with the *Aedes albopictus*–DENV and *An. gambiae*–malaria systems showing the largest shifts. Second, the parasite population thermal niche and vertebrate host population density thresholds are interdependent: Changes in temperature can elicit shifts in the vertebrate host population density thresholds and changes in vertebrate host population density affect the parasite population thermal niche. At any temperature, sustained transmission is impossible when vertebrate hosts are extremely abundant. When biting tolerance is limited, sustained transmission cannot occur at low vertebrate host population densities as well as at very high densities. In the case of unlimited biting tolerance, the parasite population thermal niche is broadest when vertebrate hosts are very rare. But when biting tolerance is limited, the thermal niche is instead narrow or nonexistent when hosts are rare. These results suggest that there is a previously unexplored relationship between vertebrate host traits and the thermal properties of mosquito-borne parasite transmission. Combined with forecasts of future climate change, improving our understanding of this relationship may lead us to more realistic predictions of the shifting global patterns of mosquito-borne disease risk.

BACKGROUND: HOST DEFENSIVE BEHAVIORS, MOSQUITO BLOOD FEEDING, AND PARASITE TRANSMISSION

Although a rich early literature investigated the effects of host defensive behaviors on mosquito blood feeding, this knowledge is absent from modern transmission models

(Reiner Jr et al., 2013; Smith et al., 2012). Here we provide a brief survey of key empirical findings.

Behavioral defenses against mosquito blood feeding

Insect bites cause pain, blood loss, infection, and disease in vertebrates, leading many vertebrate species to engage in defensive behaviors that limit their contact with biting insects (Edman & Scott, 1987). Behavioral defenses work in tandem with immunological and physiological forms of resistance and operate as the first line of defense against parasites (Hart, 1994). Defensive behaviors include swatting with tails or limbs, snapping or biting with bills or jaws, shaking or stamping of limbs, and movement and may vary by species, size, age, individual, or health status (Edman & Kale, 1971; Edman & Scott, 1987). Body size is an important determinant of both the degree of defensiveness and the effectiveness of defensive behavior: Smaller animals tend to have the strongest defenses (possibly because they suffer more from the effects of biting), while larger animals tend to be more tolerant of mosquito biting (Edman et al., 1974; Edman & Scott, 1987).

Triggers for host engagement in defensive behavior

Behavioral defenses can be costly to animals because they detract from their ability to forage or to evade predators. For example, the pausing and freezing behaviors used by Eastern chipmunks (*Tamias striatus* L.) to evade detection by predators are less effective when chipmunks engage in the more active movements necessary for behavioral defense against mosquito biting (Cully Jr et al., 1991; Walker & Edman, 1986). Because of the costs associated with behavioral defenses, animals may not be constantly vigilant against mosquito biting and may instead choose to initiate defensive behaviors once mosquito biting intensity reaches a threshold. The few studies that have measured these defensive behaviors found that defensive activity generally increased with mosquito density, but the nature of the relationship between defense and mosquito density has been largely unexplored (Cully Jr et al., 1991; Walker & Edman, 1986).

Impacts of defensive behaviors on mosquito blood feeding

Defensive behaviors have various effects on the blood-feeding cycle of mosquitoes. These behaviors reduce the rate at which an individual vertebrate is bitten by a mosquito (thereby lowering their risk of infection with a mosquito-borne parasite) (Hart, 1994). But defensive behaviors may also interrupt blood feeding, requiring that a mosquito make multiple attempts to obtain a full blood meal (Edman & Scott, 1987; Klowden & Lea, 1979; Reid et al., 2014). This increase in blood meals per gonotrophic cycle can then, in turn, lead to an increase in the overall parasite transmission rate (Davies, 1990; Klowden & Lea, 1979). Even if blood feeding is interrupted before the mosquito punctures the host blood vessel, pathogen transmission is still possible for several arboviruses that may be transmitted extravascularly, including WNV, St. Louis encephalitis virus, and Venezuelan equine encephalitis virus (Styer et al., 2007; Turell et al., 1995).

Host defensive behaviors also affect measurements of the host specificity and feeding preferences of mosquitoes. Blood meal analyses are commonly used to illuminate mosquito preferences for specific host species (Hamer et al., 2009; Kilpatrick et al., 2006). Edman, Webber, and Schmid found that mosquitoes are biased toward feeding on the most tolerant host (Edman et al., 1974). They warn that "attraction is not tantamount to feeding," imploring researchers to recognize that host defensive behaviors also play a role in determining feeding ratios (Edman et al., 1974; Edman & Kale, 1971). For example, if a mosquito is unsuccessful in initiating blood feeding due to the behavioral defenses of the host, the signature of that host will not appear in blood meal analyses. Therefore, even if a mosquito species were attracted to a defensive host species, blood meal analyses might not be able to measure the level of attraction.

Mosquitoes may be persistent in their biting even when hosts engage in defensive behaviors. This biting persistence varies by species and depends on the body size, energy state, and relative prior blood intake of the mosquito (Anderson & Brust, 1995; Davies, 1990; Reid et al., 2014). For example, whereas some species will cease blood feeding immediately upon a host engaging in defensive behavior, an *Aedes sollicitans* mosquito will not separate from the host until repletion, the volume of blood at which the mosquito freely stops feeding (Klowden & Lea, 1979). There is a cost to persistence, however: Host behavioral defenses may injure mosquitoes and lead to their death (Anderson & Roitberg, 1999; Lyimo et al., 2012).

Host defensive behaviors and parasite transmission

Infected hosts may engage in fewer defensive activities making them easier targets for mosquito blood feeding (Edman, 1989). This in turn increases the probability that a susceptible mosquito will make contact with an infected host and become infected. Likewise, infected mosquitoes may be less persistent in the face of host behavioral defenses, thereby increasing the number of contacts with distinct hosts in order to feed to repletion within a single gonotrophic cycle (Edman & Spielman, 1988). This behavior may increase the transmission rate of parasites by causing more contacts between vertebrate hosts and infectious mosquitoes.

Modeling host defensive behavior

In models, mosquito–host contact is generally represented through two interspecific contact rates: the mosquito contact rate (bites performed by an individual mosquito per unit time) and the host contact rate (bites received by an individual vertebrate per unit time) (Thongsripong et al., 2021). The form of contact needed for mosquito-borne parasite transmission depends on the direction of transmission. Successfully ingesting a blood meal, at least partially, is necessary for transmission from a vertebrate host because parasites tend to colonize their blood (Chamberlain & Sudia, 1961; Thongsripong et al., 2021). But transmission *to* a vertebrate host typically only requires that the mosquito probe the vertebrate host's skin because parasites colonize the salivary glands of mosquitoes (Chamberlain & Sudia, 1961; Graumans et al., 2020; Thongsripong et al., 2021).

Several factors affect mosquito and host contact rates. The mosquito contact rate is primarily determined by the rate at which mosquitoes proceed through their gonotrophic cycle and is limited by host abundance and the ability of the mosquito to detect and feed on hosts undisturbed (Scott & Takken, 2012). The host contact rate is determined by the population density and feeding rate of mosquitoes and is limited by the behavioral defenses of the host. The overall contact rate (the total number of bites in the host–mosquito system per unit time) should therefore depend on the traits, behaviors, and abundances of both the mosquito and the host.

We denote the mosquito contact rate by b_V and the host contact rate by b_H. The maximum mosquito contact rate and maximum host contact rate are denoted by σ_V and σ_H, respectively. The mosquito and host population densities are denoted by V and H, respectively. The formulation used for the interspecific contact rates is determined by whether vertebrate host biting tolerance is (1) limited, as in the Chitnis dynamic contact rate model, or (2) unlimited, as in the Ross–Macdonald model (Chitnis et al., 2006; Reiner Jr et al., 2013; Thongsripong et al., 2021). While we focus on these two models, they are not the only ways of modeling the effect of host biting tolerance on the contact rates between biting flies and their hosts (Haufe, 1987). We chose to focus on the Chitnis model because it is quite similar to the Ross–Macdonald model (incorporating only one additional parameter) and has been used to model several systems of mosquito-borne parasite transmission (Chitnis et al., 2006, 2013; Manore et al., 2014, 2017).

For the Chitnis dynamic contact rate model (Chitnis et al., 2006), the contact rates are given by

$$b_V = \sigma_V \left(\frac{\sigma_H H}{\sigma_H H + \sigma_V V} \right), \tag{1}$$

$$b_H = \sigma_H \left(\frac{\sigma_V V}{\sigma_H H + \sigma_V V} \right). \tag{2}$$

This model has been used to explore the dynamics of malaria (Chitnis et al., 2006), Rift valley fever (Chitnis et al., 2013), dengue, zika, and chikungunya (Manore et al., 2014, 2017). In this model, σ_H represents the biting tolerance threshold, which serves as an upper limit to the vertebrate host biting rate, b_H (Thongsripong et al., 2021). The host contact rate b_H approaches σ_H when the biting pressure of mosquitoes ($\sigma_V V$) is high or when the vertebrate host population density (H) is low. Similarly, the mosquito contact rate b_V approaches its maximum, σ_V, when the vertebrate host availability ($\sigma_H H$) is high or when the mosquito population density (H) is low.

In the case of unlimited biting tolerance, vertebrate hosts tolerate any level of biting by mosquitoes. The contact rates in this case are obtained by taking the limit of the contact rates (2) and (1) as the biting tolerance, σ_H, approaches infinity. Equations (3) and (4) then give the contact rates for this case:

$$b_V^{RM} = \lim_{\sigma_H \to \infty} b_V = \sigma_V, \tag{3}$$

$$b_H^{RM} = \lim_{\sigma_H \to \infty} b_H = \sigma_V \left(\frac{V}{H} \right), \tag{4}$$

where the superscript "RM" is used to indicate that these contact rates are identical to those commonly used in the Ross–Macdonald model (Smith et al., 2012, 2014). The Ross–Macdonald contact rate model is therefore a special case of the Chitnis dynamic contact rate model. Note that, in many cases, modelers assume that the ratio of mosquito and host abundances, V/H, is a fixed constant, m (Reiner Jr et al., 2013; Smith et al., 2012). In this case, the vertebrate host biting rate, b_H^{RM}, is, unrealistically, unbounded when the vertebrate host population density, H, decreases to zero.

Figure 1 illustrates how the interspecific contact rates of the Chitnis and Ross–Macdonald models differ with respect to mosquito and host population densities. In the Ross–Macdonald model, the mosquito contact rate is constant (Figure 1a,b, blue line). In contrast, the mosquito contact rate in the Chitnis dynamic model exhibits a saturating increasing and decreasing relationship to host and mosquito population densities, respectively (Figure 1a,b, pink line). In both models, the host contact rate (Figure 1c,d) is inversely proportional to host population density and directly proportional to mosquito population density. But in the Ross–Macdonald model, the host contact rate is unbounded as host density approaches zero (Figure 1c, blue line).

METHODS

Model

To examine the relationship between the traits of the mosquito vector, vertebrate host, and parasite to the transmission potential of the system, we created a core compartmental model of mosquito-borne parasite transmission (Figure 2). In all of the following equations, temperature-dependent quantities are indicated as functions of temperature, T (i.e., $p = p(T)$). The system is divided into populations of vertebrate hosts (labeled with subscript H) and mosquitoes (labeled with subscript V). The full description of the model formulation is given in Appendix S1.

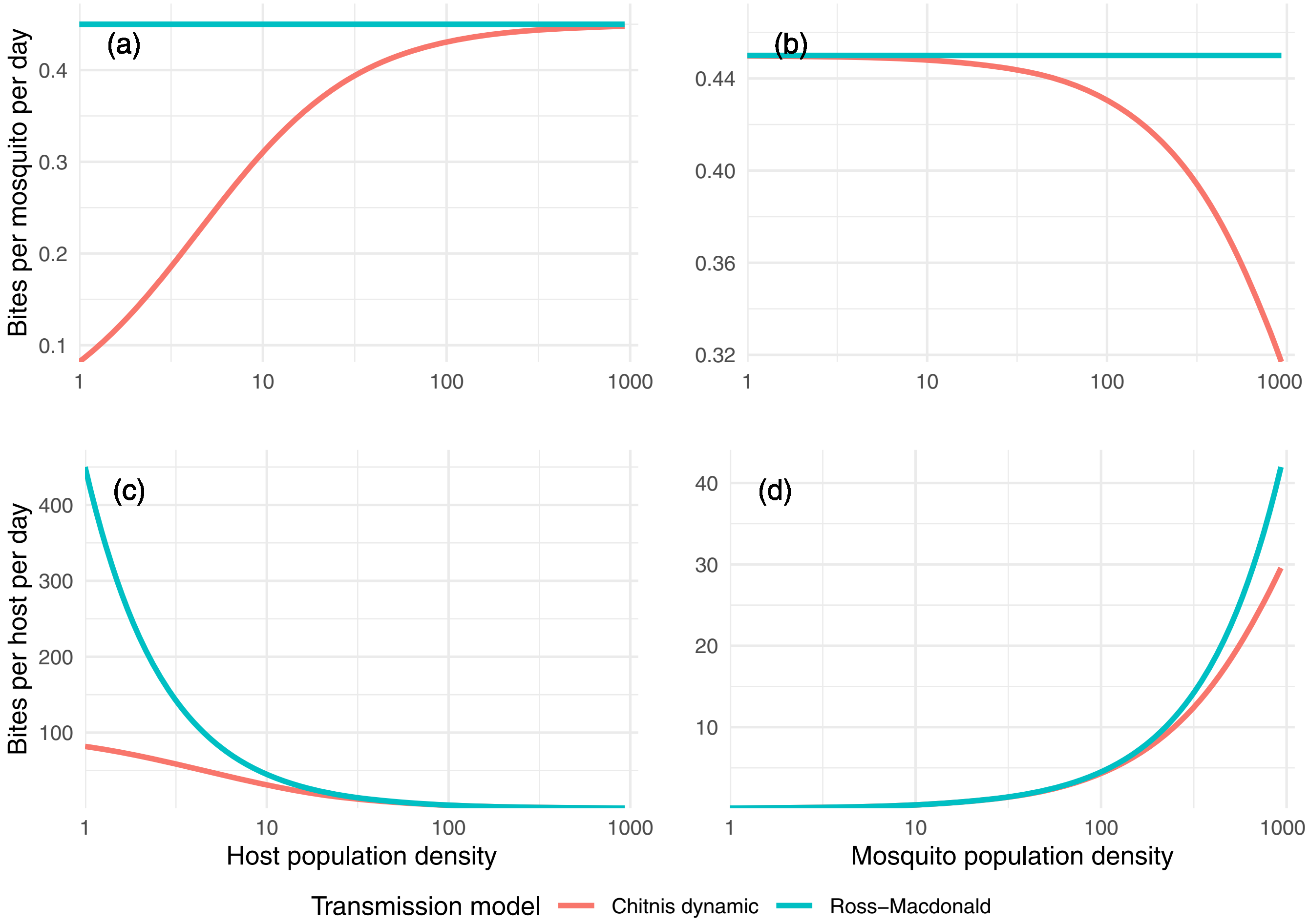

FIGURE 1 Comparison of Chitnis dynamic contact rate and standard Ross–Macdonald contact rate models. In the left columns, mosquito population is held constant, while in the right columns host population density is held constant. Upper panel: In the Ross–Macdonald model, the mosquito biting rate is constant with respect to both host and mosquito population density (a and b, blue lines) while in the Chitnis model mosquito biting increases with host population density (a, red curve) and decreases with mosquito population density (b, red curve). Lower panels: The relationships between the number of bites that a host receives per day and host and mosquito densities diverge at low host population densities (c) and, to a lesser extent, at high mosquito densities (d). For plots (a) and (c), mosquito population density is fixed at 1000 individuals per square kilometer. For plots (b) and (d), host population density is fixed at 10 individuals per square kilometer. Maximum mosquito biting rate is 0.45 bites per mosquito per day and maximum host biting rate is 100 bites per host per day. Mosquito and host population densities are plotted on a logarithmic scale.

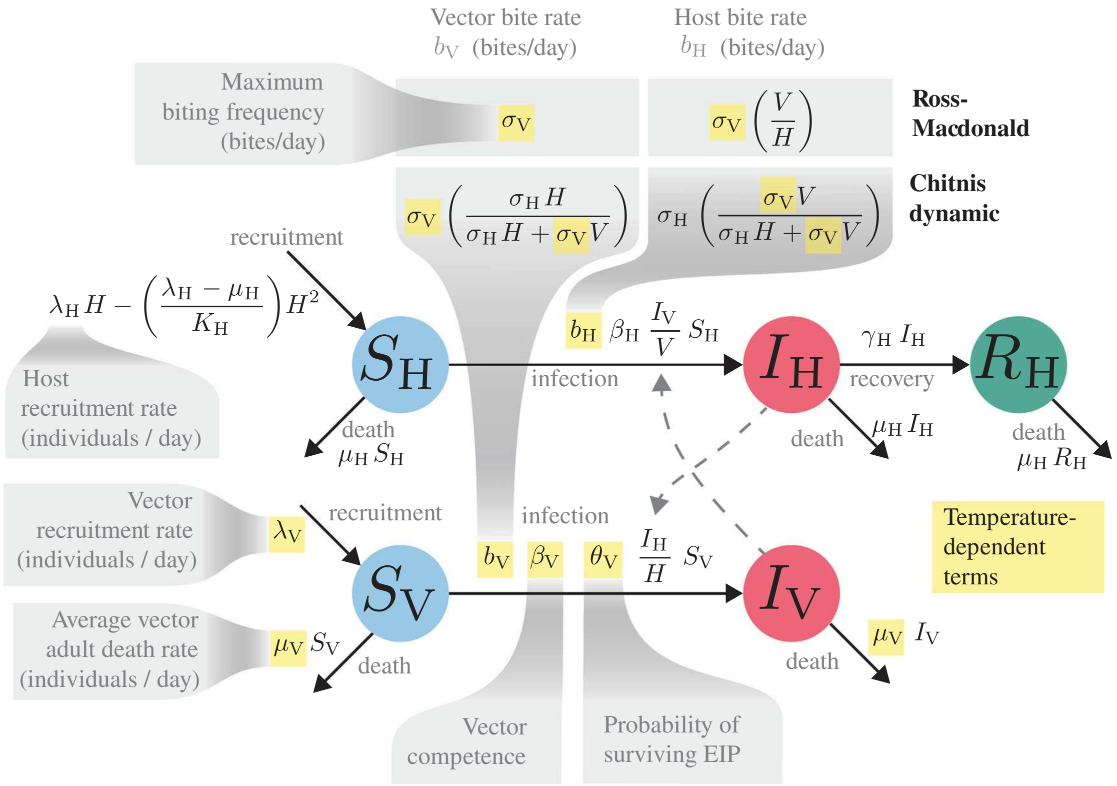

FIGURE 2 Flow diagram for core model of mosquito-borne pathogen transmission between vertebrate host and mosquito populations including temperature-dependent mosquito parameters. The vertebrate host population exhibits susceptible-infected-recovered infection dynamics, and the mosquito population exhibits susceptible-infected dynamics. Susceptible hosts (S_H) may become infectious (I_H) upon contact with an infectious vector (I_V) and then move to the recovered compartment (R_H) after their infectious period. Susceptible mosquitoes (S_V) may become infected (I_V) after contact with an infectious host (I_H) after surviving the extrinsic incubation period (EIP) with probability θ_V. Infectious mosquitoes remain infectious for the duration of their lifespan, primarily because mosquito lifespans are too short to clear a viral infection (Beier, 1998; Gibbons & Vaughn, 2002; Hopkins et al., 2022). Black lines represent transitions into and out of compartments, and gray dotted lines indicate contributions to transmission. Mosquito recruitment is also dependent on temperature through a submodel for the aquatic-stage population in Equations (S1.7) and (S1.8) in Appendix S1. The functions b_H and b_V represent the per-capita interspecific contact rates of vertebrate hosts and mosquitoes, respectively. The exact functional forms for these rates depend on whether the Ross–Macdonald or Chitnis dynamic contact rate formulation is used.

The demographic model for the vertebrate hosts follows a logistic equation with carrying capacity K_H and intrinsic growth rate $\lambda_H - \mu_H$. Vertebrate hosts are fed upon by mosquitoes at the per-capita host contact rate, b_H, as described earlier. If a susceptible vertebrate host (S_H) comes into contact with an infected mosquito (which occurs with probability I_V/V), then the vertebrate host will become infected with probability β_H. Infectious hosts (I_H) move to the recovered compartment (R_H) at the per-capita recovery rate γ_H and remain immune for the remainder of their lives. The total vertebrate host population is denoted by $H = S_H + I_H + R_H$.

Susceptible mosquitoes (S_V) are recruited at the rate $\lambda_V(T)$. To incorporate temperature-dependent traits of immature mosquitoes, we derived $\lambda_V(T)$ from a submodel of immature mosquito population dynamics following Agusto et al. (2015). We compute $\lambda_V(T)$ by assuming that the immature mosquito equation is at a positive equilibrium. As a modification of past models parameterized from TPCs (Mordecai et al., 2013; Parham & Michael, 2010), this recruitment model accounts for the fact that the total egg recruitment rate depends on the abundance of adult female mosquitoes.

When a susceptible mosquito (S_V) feeds on an infected vertebrate host (I_H), it will become exposed to the pathogen with probability $\beta_V(T)$. With probability $\theta_V(T) = \exp(-\mu_V(T)/\eta_V(T))$, exposed mosquitoes will survive the extrinsic incubation period and become infectious (I_V), remaining so for the remainder of their lives. The total mosquito population is denoted by $V = S_V + I_V$. At equilibrium, the total mosquito population is given by Equation (5):

$$V^*(T) = \frac{\rho_L(T) K_L}{\mu_V(T)} \left(1 - \frac{\mu_V(T)}{\sigma_V(T) f(T) \delta_L(T)}\right). \tag{5}$$

Here, $f(T)$ is the average number of female eggs laid in a single oviposition, $\rho_L(T)$ is the immature mosquito development rate, $\delta_L(T)$ is the probability of immature mosquito survival to adulthood, and K_L is the immature mosquito carrying capacity.

The interspecific contact rates, b_H and b_V, are given by either of Equations (1) and (2) or (3) and (4) and illustrated in Figure 1, depending on whether biting tolerance is limited or unlimited, respectively.

Parameterization

We parameterized the model for five systems of mosquito-borne pathogen transmission. Multiple systems are modeled to investigate how traits particular to the mosquito and parasite species in the system have an impact on how host traits relate to the thermal properties of transmission. The systems that we consider are *Ae. aegypti*–DENV, *Ae. aegypti*–ZIKV, *Ae. albopictus*–DENV, *An. gambiae*–*P. falciparum*, and *Cx. quinquefasciatus*–WNV.

We selected these specific systems for three reasons. First, the pathogens cause diseases of current and future risk to human populations (Bhatt et al., 2013; Gething et al., 2011; Kilpatrick, 2011; Puntasecca et al., 2021; Ryan et al., 2019). Second, animal reservoirs play a role in these transmission systems to varying extents (Faust & Dobson, 2015; Kramer et al., 2019; Rondón et al., 2019; Valentine et al., 2019; Wolfe et al., 2007). Finally, there are sufficient data available to derive reliable TPCs of mosquito and parasite parameters for these systems (Mordecai et al., 2013, 2017, 2019; Shocket et al., 2018, 2020; Tesla et al., 2018; Villena et al., 2022). We chose two systems with the same vector (*Ae. aegypti*–DENV, *Ae. aegypti*–ZIKV) and two with the same pathogen (*Ae. aegypti*–DENV, *Ae. albopictus*–DENV) to facilitate making comparisons regarding the relative impact of the identity of the parasite or mosquito species in the system, respectively. Following Mordecai et al. (2013) and Villena et al. (2022), we used composite *Anopheles* spp. trait data to form TPC estimates due to a lack of data for species in the *An. gambiae* complex, the primary vector of human malaria. We also incorporated more recent data on the effects of temperature on *Anopheles* spp. fecundity (Aytekin et al., 2009; Christiansen-Jucht et al., 2015). The sources for all the temperature trait data used in this study are listed in Appendix S2: Tables S1–S3, organized by mosquito species and traits.

Trait TPCs were derived from published laboratory data following the Bayesian approach described in Johnson et al. (2015), which we briefly summarize here. For each system and trait, a functional form for the TPC was assigned: linear, quadratic, or Brière. Next, using the available data, posterior distributions for the TPC hyperparameters were derived through a Gibbs sampling process. Samples were taken from these posterior distributions to create trait TPCs for each system. From these samples, for a given temperature, we obtained a distribution of values of a given trait or other quantity of interest. Unless otherwise specified, all quantities of interest, such as the basic reproduction number or parasite population thermal niche width, are reported as their median with respect to the samples from the trait TPC hyperparameter posterior distributions. We assume that the immature mosquito carrying capacity, K_L, is a constant value of 300 individuals per hectare as we lack data on the thermal response of this parameter, and this value resulted in a plausible range of values for overall mosquito population density (Appendix S2: Figure S1).

Figure 3 shows adult mosquito lifespan, maximum biting frequency, eggs per female per day, immature development rate, the probability of an immature mosquito surviving to adulthood, the probability of an infected mosquito surviving the extrinsic incubation period (EIP), and vector competence as a function of temperature for each of the five systems we considered. As with previously reported TPCs (Mordecai et al., 2013, 2017, 2019; Shocket et al., 2020; Tesla et al., 2018), we took the probability of surviving the EIP to be a function of the parasite development rate $\eta_V(T)$ and adult mosquito mortality rate $\mu_V(T)$: $\theta_V(T) = \exp(-\mu_V(T)/\eta_V(T))$. All remaining mosquito parameters are independent of other parameters. To address the key questions posed in this study, we varied two key vertebrate host parameters: population density and biting tolerance. All other parameters remained fixed and are listed in Table 1. Vertebrate host population density was varied across several orders of magnitude on a logarithmic scale to cover a wide range of population sizes. We also varied the biting tolerance threshold parameter, σ_H, on a logarithmic scale, including a point at infinity for the unlimited biting tolerance case.

Mathematical analysis

We measured the outbreak and sustained transmission potential of a system through its basic reproduction number, $\mathcal{R}_0$. Higher values of $\mathcal{R}_0$ lead to larger initial outbreak sizes and higher equilibrium prevalence (see Appendix S1: Section S2 for details). When $\mathcal{R}_0 > 1$, the parasite population persists within the system indefinitely (Diekmann et al., 1990; van den Driessche & Watmough, 2002). $\mathcal{R}_0$ was calculated via the method of van den Driessche and Watmough (2002). We assumed that vertebrate host and mosquito populations were

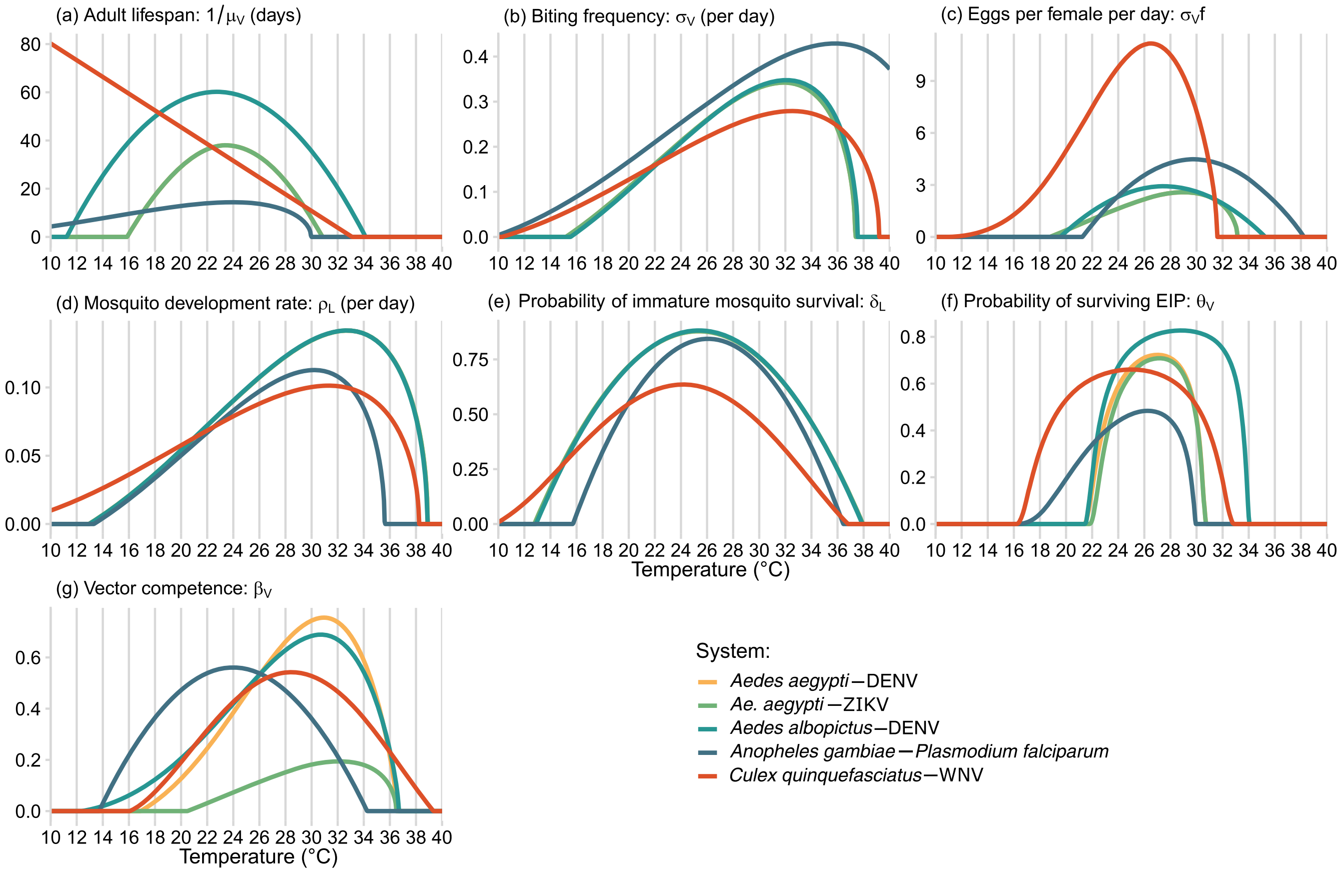

FIGURE 3 Thermal performance curves (TPCs) for the mosquito and parasite traits used in our model: (a) adult lifespan, (b) maximum biting frequency, (c) eggs per female per day, (d) mosquito development rate, (e) the probability of immature mosquito survival, (f) the probability of surviving the extrinsic incubation period, and (g) vector competence. Curves are shown in color for each of the five systems we considered. Temperatures vary from 10 to 35°C to encompass the full thermal niche of all mosquito species considered in this study (defined as the range of temperatures at which all traits for a given species are positive). Each trait is a unimodal function of temperature except for the lifespan of *Culex quinquefasciatus* in (a). The *Aedes aegypti*–DENV and *Ae. aegypti*–ZIKV maximum biting frequency (b) curves overlap because infection is assumed to not affect these traits (but see Tesla et al. [2018]). All functions and parameters for generating these curves are derived from Mordecai et al. (2013, 2017, 2019), Tesla et al. (2018), Shocket et al. (2020), and Villena et al. (2022). Shown here are the median values of the mosquito traits with respect to their TPC hyperparameter posterior distributions. A full description of how these curves were obtained is available in Appendix S1: Section S1.

initially at their carrying capacities and fixed all parameters as described in the previous subsection.

$\mathcal{R}_0 = \mathcal{R}_0(T, K_H, \sigma_H)$ is a function of temperature T in degrees Celsius, vertebrate host population density K_H in individuals per hectare, and vertebrate host biting tolerance σ_H in bites per host per day. Due to the Bayesian parameter fitting process used to derive trait TPCs, we numerically obtained $\mathcal{R}_0$ as a distribution across trait TPC hyperparameter samples. We varied vertebrate host availability by modifying biting tolerance, σ_H, and population density, K_H, independently.

We first determined whether $\mathcal{R}_0$ had the properties of a TPC: a function of temperature that is supported on a single bounded interval that has a unique intermediate mode (Angilletta, 2006; Huey & Kingsolver, 1989; Huey & Stevenson, 1979). To do this, we calculated $\mathcal{R}_0$ as a function of temperature and other parameters. Then, to visually verify that $\mathcal{R}_0$ had a unique maximum and was nonzero on a single finite interval, we plotted $\mathcal{R}_0$ against temperature for each system and across the full range of values of vertebrate host population density and biting tolerance (Figure 4).

The bounded interval support of a TPC is also called the thermal tolerance range (Huey & Stevenson, 1979) or thermal niche (Huxley et al., 2022; Ryan et al., 2019). We define the parasite population thermal niche to be the set of temperatures at which $\mathcal{R}_0$ exceeds one, that is, the temperatures at which transmission is expected to be sustained and outbreaks are possible. The lower endpoint of the parasite population thermal niche is the critical thermal minimum, CT_{min}, and its upper endpoint is the critical thermal maximum, CT_{max}. We also considered the width of the parasite population thermal niche, $CT_{width} = CT_{max} - CT_{min}$. When $\mathcal{R}_0$ was less than one at

TABLE 1 Vertebrate host parameter values for model governed by system of Equations (S1.1) in Appendix S1.

Parameter	Description	Value(s)
K_{H}	Carrying capacity (individuals/ha)	Varied from 10^{-2} to 10^4
σ_{H}	Biting tolerance threshold (bites per host per day)	Varied from 1 to 10^3 (infinite in the case of the Ross–Macdonald contact model)
λ_{H}	Recruitment rate (1/day)	0.005
μ_{H}	Mortality rate (1/day)	1/(365 × 20)
β_{H}	Probability of becoming infected after being bitten by an infectious mosquito	0.25
γ_{H}	Recovery rate (1/day)	1/5

all temperatures considered, $\mathrm{CT_{min}}$ and $\mathrm{CT_{max}}$ had no biological meaning and $\mathrm{CT_{width}}$ was set to zero. The thermal optimum, T_{opt}, is the temperature at which the unique maximum of $\mathcal{R}_0$ is achieved. Note that, because $\mathcal{R}_0$ is also a function of vertebrate host availability (K_{H} and σ_{H}), $\mathrm{CT_{min}}$, $\mathrm{CT_{max}}$, and T_{opt} may also depend on vertebrate host availability.

To estimate the maximum difference between T_{opt} values when biting tolerance is limited and unlimited, we calculated T^0_{opt}, the transmission thermal optimum when vertebrate hosts are completely unavailable, calculated through Equation (6):

$$T^0_{\mathrm{opt}} = \lim_{\sigma_{\mathrm{H}} K_{\mathrm{H}} \to 0} T_{\mathrm{opt}}(K_{\mathrm{H}}, \sigma_{\mathrm{H}}). \tag{6}$$

The maximum difference in T_{opt} between the unlimited and limited biting tolerance cases can then be computed as $T^{\mathrm{RM}}_{\mathrm{opt}} - T^0_{\mathrm{opt}}$.

Because of the highly nonlinear temperature dependence of mosquito and parasite parameters, we are not able to directly compute $\mathrm{CT_{min}}$, $\mathrm{CT_{max}}$, or T_{opt}. Instead, we numerically estimated these quantities in R by calculating $\mathcal{R}_0(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$ across a gradient of temperature, vertebrate host population density, and biting tolerance values for each sample from the mosquito trait TPC hyperparameter posterior distribution. Temperature was varied from 10 to 40°C, to cover the full range of temperatures at which mosquito and parasite TPCs are positive (Figure 3). Vertebrate host population density and biting tolerance were varied as described in Table 1. Numerically, $\mathrm{CT_{min}}$ ($\mathrm{CT_{max}}$) is the coolest (warmest) temperature at which $\mathcal{R}_0(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$ exceeds one. T_{opt} is then the temperature associated with the largest value of $\mathcal{R}_0(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$. Uncertainty in mosquito traits induced distributions for $\mathrm{CT_{min}}$, $\mathrm{CT_{max}}$, and T_{opt} that vary with vertebrate host population density and biting tolerance (Appendix S2: Figure S8).

To determine whether vertebrate host availability limits parasite population persistence, we also calculated the values of vertebrate host population density at which $\mathcal{R}_0$ exceeded one. We were motivated to consider this possibility because, in the Ross–Macdonald model, $\mathcal{R}_0$ decreases and approaches zero as vertebrate host population density is increased (Keeling & Rohani, 2008). We refer to such a threshold as an upper critical host community size, $\mathrm{CH_{max}}$. If $\mathcal{R}_0$ also decreases below one as vertebrate host population density decreases, we define a lower critical host community size, $\mathrm{CH_{min}}$, to be the smallest value of K_{H} such that $\mathcal{R}_0$ is greater than one. Since $\mathcal{R}_0$ is also a function of temperature, $\mathrm{CH_{max}}$ and $\mathrm{CH_{min}}$ may themselves depend on temperature. By setting $\mathcal{R}_0 = \mathcal{R}_0(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$ equal to one and solving for K_{H}, we derived formulas for $\mathrm{CH_{min}}$ and $\mathrm{CH_{max}}$ directly as functions of the other model parameters (Appendix S1: Section S3.2).

Sensitivity and uncertainty analyses

Following Mordecai et al. (2013), we calculated the local sensitivity of $\mathcal{R}_0$ to temperature as well as the contributions of the temperature-dependent mosquito traits to this overall sensitivity, $\mathcal{S}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$, given by Equation (7):

$$\mathcal{S}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}}) = \frac{1}{\mathcal{R}_0(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})} \frac{\partial \mathcal{R}_0(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})}{\partial p} \frac{dp}{dT}, \tag{7}$$

where p is a mosquito temperature-dependent trait. Note that we only define $\mathcal{S}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$ at temperatures where $\mathcal{R}_0(T) > 0$. $\mathcal{S}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$ was calculated for each sample from the TPC hyperparameter posterior distributions and reported as the median value across all the samples (Appendix S2: Figure S9). The quantity $\mathcal{S}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})$ is related to T_{opt} through the relation $\sum_t \mathcal{S}_t\left(T_{\mathrm{opt}}, K_{\mathrm{H}}, \sigma_{\mathrm{H}}\right) = 0$. To facilitate a comparison of the differences in the temperature sensitivity of $\mathcal{R}_0$ across systems, we also computed the proportional absolute contribution of each trait to overall local sensitivity as in Equation (8):

$$\overline{\mathcal{S}}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}}) = \frac{|\mathcal{S}_p(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})|}{\sum_t |\mathcal{S}_t(T, K_{\mathrm{H}}, \sigma_{\mathrm{H}})|}, \tag{8}$$

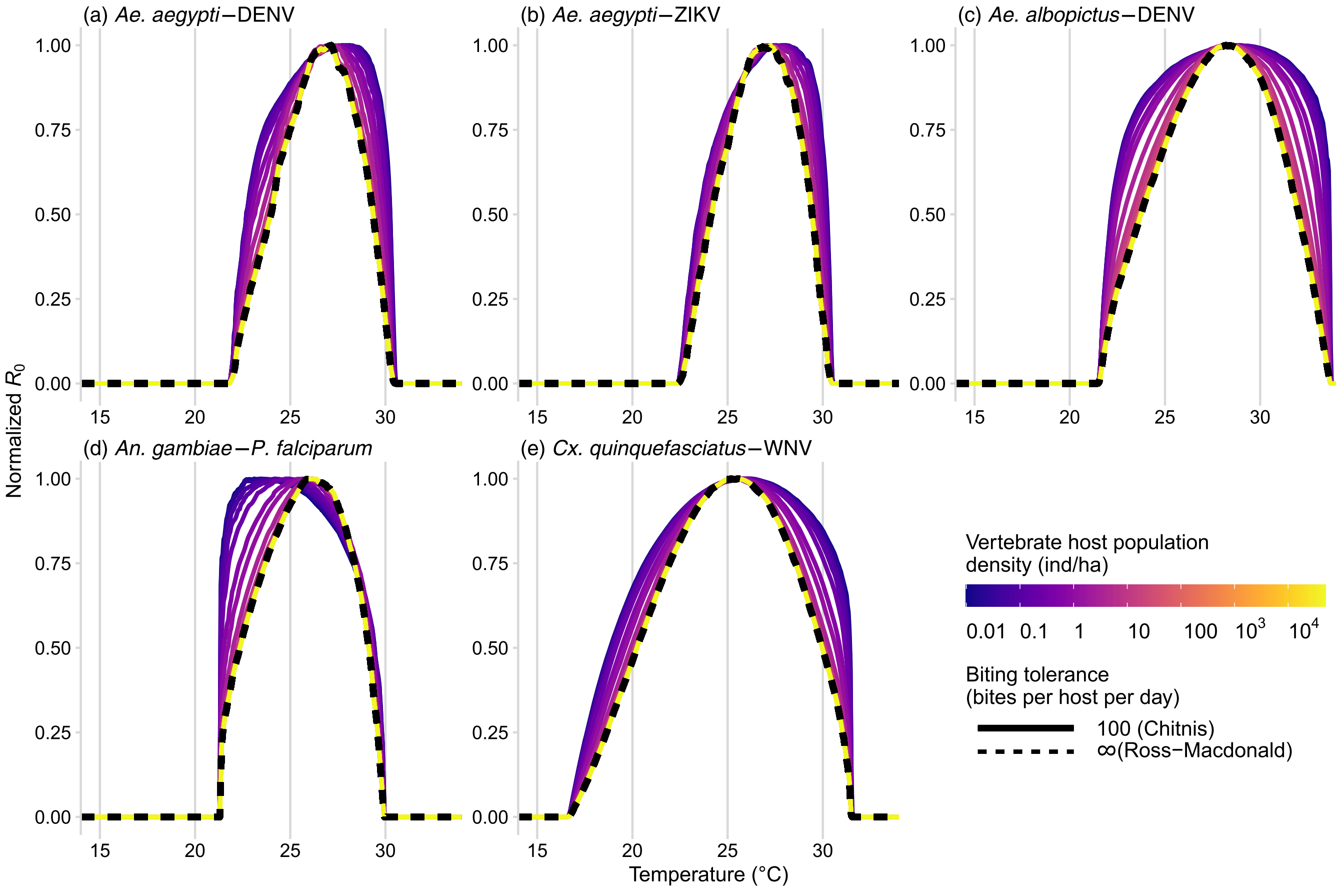

FIGURE 4 $\mathcal{R}_0$ as a function of temperature has the usual properties of a thermal performance curve (TPC): It is positive on a single bounded interval and has a unique maximum value. The shape of the $\mathcal{R}_0$ TPC depends on vertebrate host availability and the mosquito–parasite system. The shape of the thermal response of $\mathcal{R}_0$ derived from the Ross–Macdonald model (dotted black curves) is independent of vertebrate host population density, while those derived from the Chitnis dynamic model are dependent on vertebrate host population density (solid lines in color). Shown here are the median values of $\mathcal{R}_0$ with respect to the mosquito trait TPC posterior distributions. $\mathcal{R}_0$ is normalized by dividing by its maximum value in each system, for the given value of biting tolerance and vertebrate host population density. Vertebrate host population density is varied on a $\log_{10}$ scale.

where the sum is over each temperature-dependent trait, t. We normalized by the sum of the absolute values instead of the regular sum to avoid a singularity when $T = T_{\text{opt}}$. Finally, to explore how host traits might impact the importance of temperature-dependent mosquito traits, we calculated the change in the contributions of each trait to overall local sensitivity as K_H is varied from 1 to 100, shown in Figure 7.

Following Johnson et al. (2015), we also performed uncertainty analyses using the posterior samples derived from the Bayesian fitting process for the mosquito trait TPCs. Uncertainty analyses were conducted for T_{opt}, $\text{CT}_{\min}$, $\text{CT}_{\max}$, and CT_{width} with respect to each of the temperature-dependent mosquito life history traits (Appendix S2: Figures S10–S13). Uncertainty was measured as the relative change in the highest posterior density interval (HPD) width of each of these quantities of interest. First, the 95% HPD width of the given quantity of interest was calculated when all mosquito life history traits were allowed to vary across TPC samples. Then, HPD width was calculated with all but a focal life history trait set to its posterior mean. The ratio of the former quantity to the latter represents the amount of change in the posterior distribution of the quantity of interest attributed to changes in the focal variable. We obtained uncertainty results across a range of values for temperature, vertebrate host population density, and biting tolerance. Note that this form of uncertainty analysis only provides information on the relative degree of influence of a given trait on a quantity of interest, not on the direction of the influence.

All analysis was conducted in R (R Core Team, 2021). All data and code necessary for reproducing our analyses are available at https://github.com/DrakeLab/thermal-properties-mbps.

RESULTS

$\mathcal{R}_0$ is a function of temperature and vertebrate host availability

The basic reproduction number, $\mathcal{R}_0$, was computed as a function of temperature and vertebrate host availability across five mosquito–parasite systems. The expression of $\mathcal{R}_0$ is given as follows by Equation (9):

$$\mathcal{R}_0 = \sigma_V \left(\frac{\sigma_H K_H}{\sigma_H K_H + \sigma_V V^*} \right) \sqrt{\left(\frac{V^*}{K_H} \right) \beta_V \theta_V \left(\frac{1}{\gamma_H + \mu_H} \right) \beta_H \left(\frac{1}{\mu_V} \right)}, \tag{9}$$

where V^* is the temperature-dependent density of adult mosquitoes at the disease-free equilibrium. Vertebrate host parameter values are as in Table 1. The parameters σ_V, V^*, β_V, η_V, and μ_V are all functions of temperature, as shown in Figure 3.

We make a few initial observations about $\mathcal{R}_0$ as a function of host availability (K_H and σ_H). First, $\mathcal{R}_0$ strictly increases with vertebrate host biting tolerance (σ_H). Second, as discussed above, this model is equivalent to the Ross–Macdonald model when biting tolerance approaches infinity, as shown in Equation (10):

$$\mathcal{R}_0^{\mathrm{RM}} = \sigma_V \sqrt{\left(\frac{V^*}{K_H} \right) \beta_V \theta_V \left(\frac{1}{\gamma_H + \mu_H} \right) \beta_H \left(\frac{1}{\mu_V} \right)}. \tag{10}$$

Taken together, these formulas imply that the $\mathcal{R}_0$ of the Ross–Macdonald model is always greater than the $\mathcal{R}_0$ obtained from our model. Finally, regardless of whether σ_H is finite or infinite, $\mathcal{R}_0$ eventually decreases with vertebrate host population density (Appendix S1: Section S3.1). In fact, $\mathcal{R}_0$ approaches zero as vertebrate host population density approaches infinity, ensuring the existence of an upper critical host community size, $\mathrm{CH}_{\mathrm{max}}$.

Figure 4 shows how $\mathcal{R}_0$ varies as a function of temperature. Note that in Figure 4, $\mathcal{R}_0$ has been normalized by its maximum value to emphasize the relative (as opposed to absolute) changes in $\mathcal{R}_0$ with respect to temperature. $\mathcal{R}_0$ has the expected properties of a TPC: It has a unique intermediate mode and is positive on a single bounded interval. This holds in all the systems we considered and across the full range of vertebrate host population density. The equations for the thermal optimum, T_{opt}, and thermal extrema, $\mathrm{CT}_{\mathrm{min}}$ and $\mathrm{CT}_{\mathrm{max}}$, are therefore well defined. $\mathcal{R}_0$ varies in absolute terms with respect to temperature and vertebrate host availability across each of the five systems (Appendix S2: Figure S2).

The traits that most strongly determine the local temperature sensitivity of $\mathcal{R}_0(T)$ change substantially as temperature and vertebrate host availability are varied (Appendix S2: Figure S9). Reflecting the unimodal shape of $\mathcal{R}_0(T)$, the temperature sensitivity of $\mathcal{R}_0(T)$ monotonically decreases. At cooler temperatures, the temperature sensitivity of $\mathcal{R}_0(T)$ is mostly determined by the positive association between temperature and parasite development rate, vector competence, or biting frequency. On the other hand, universally across all five systems, adult mortality rate induces a strong negative relationship between $\mathcal{R}_0(T)$ and temperature at warmer temperatures.

The overall temperature sensitivity of $\mathcal{R}_0(T)$ is generally lessened at lower levels of host availability (Appendix S2: Figure S9, first row). In this case, we observe a notable difference between the systems. In the *An. gambiae–P. falciparum* system, each trait contributes much less to the positivity of overall $\mathcal{R}_0(T)$ temperature sensitivity (Appendix S2: Figure S9, first row [d]). This leads the overall temperature sensitivity of $\mathcal{R}_0(T)$ to reach zero at much cooler temperatures than in the other systems and, indeed, than when host availability is much higher in the *An. gambiae–P. falciparum* system.

To more closely examine this difference, we measured how the contributions of the traits to overall $\mathcal{R}_0(T)$ temperature sensitivity changed as host population density was increased from 1 to 100 individuals per hectare (Figure 7). The pattern of changes in trait importance is fairly similar in all the systems except for *An. gambiae–P. falciparum*. In these other systems, the importance of biting frequency and adult mortality rate are most increased at cooler and warmer temperatures, respectively (Figure 7a–c,e). Additionally, immature development rate and vector competence decrease in importance, particularly near the middle of the thermal niche, while parasite development rate consistently decreases in importance throughout the thermal niche. Finally, eggs per female per day and the probability of immature survival, both of which refer to aquatic stage mosquito life history, do not meaningfully change in their importance when host availability is increased.

The results for *An. gambiae–P. falciparum* differ in several key ways (Figure 7d). First, the importance of biting frequency is elevated more at cooler temperatures than in the other systems. Second, instead of remaining flat, the importance of the parasite development rate exhibits its greatest decrease at the lower edge of the thermal niche. Finally, instead of attaining its minimum at nearly the same temperature as vector competence, the change in importance of the immature development rate has a trough at a much cooler temperature. Taken together, this distinct pattern in how host availability shifts the importance of the various mosquito life history traits in relation to the temperature sensitivity of $\mathcal{R}_0(T)$ may give rise to the observed differences in thermal property results for the *An. gambiae–P. falciparum* system.

Transmission thermal optimum and vertebrate host availability

Figure 4 shows that the transmission thermal optimum, T_{opt}, may depend on vertebrate host availability (solid lines). Unlike when biting tolerance is unlimited (the Ross–Macdonald model), T_{opt} depends on vertebrate host availability when biting tolerance is limited. It can be shown analytically that T_{opt} derived from the Chitnis contact model is always dependent on host availability and in particular host density, a marked difference from past works exploring the thermal optima of mosquito-borne diseases (Appendix S1: Equation S4.3 and Section S4.2). To better illustrate the dependence of T_{opt} on vertebrate host availability when biting tolerance is limited, we plotted T_{opt} against vertebrate host population density and biting tolerance across each of the five systems in Figure 5. We show these curves across a wide range of vertebrate host population densities to illustrate their full behavior, noting that real animal populations usually have densities on the order of only 0.1 to 100 individuals per hectare. Appendix S2: Figures S3 and S4 show the relationships between T_{opt} and vertebrate host population density and biting tolerance, respectively.

T_{opt} is a sigmoidal function of the logarithm of vertebrate host population density, decreasing in most systems (e.g., Appendix S2: Figure S3a–c,e) and increasing in one (e.g., Appendix S2: Figure S3d). The amount of variation differs significantly across systems, with some exhibiting very little change (Figure 5a–c,e) and one showing variation exceeding 5°C (Figure 5d). As was determined analytically, when biting tolerance is unlimited, T_{opt} is constant with respect to vertebrate host population density (Figure 5, upper panel of each plot). As biting tolerance or vertebrate host population density is increased,

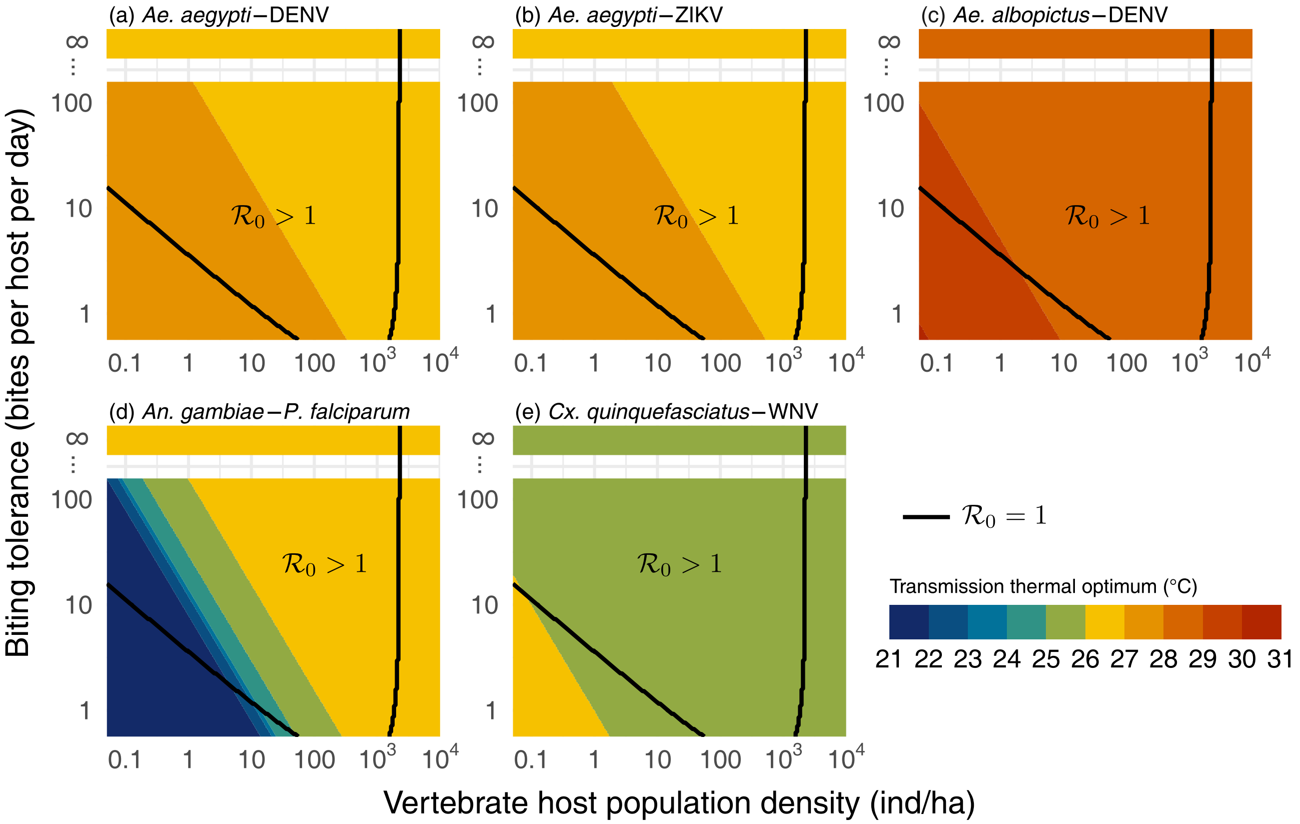

FIGURE 5 The thermal optimum for transmission, T_{opt}, may be sensitive to vertebrate host population density and biting tolerance. Here, T_{opt} is plotted as a function of vertebrate host population density and biting tolerance for each of the five systems. In the Ross–Macdonald model, where biting tolerance is assumed to be infinite, T_{opt} is independent of vertebrate host population density (upper bars in plots). But when biting tolerance is limited, T_{opt} can vary as much as 5°C (d). T_{opt} may increase (d) or decrease (a–c, e) as vertebrate host population density or biting tolerance is increased. Shown here are the median values of T_{opt} with respect to the mosquito trait thermal performance curve posterior distributions. Both biting tolerance and vertebrate host population density are varied on a $\log_{10}$ scale. $\mathcal{R}_0 > 1$ in the region contained within the black $\mathcal{R}_0 = 1$ curve. All remaining parameters are given in Table 1 and Figure 3.

T_{opt} approaches the constant value obtained from using the Ross–Macdonald model. This can be seen more clearly in Appendix S2: Figure S3 (black lines) and Appendix S2: Figure S4 (dark blue lines).

Table 2 shows the value of T_{opt} in the unlimited biting tolerance case ($T^{\text{RM}}_{\text{opt}}$) and when vertebrate host availability is near zero (T^{0}_{opt}). The difference of these two values represents the maximum amount of change in T_{opt} due to reduced host availability. Each of the values in Table 2 is independent of vertebrate host parameters and determined solely by mosquito and parasite parameters. *An. gambiae*–*P. falciparum* shows the greatest increase in T_{opt} due to changes in host availability, whereas *Ae. aegypti*–DENV shows the greatest decrease. However, T_{opt} for the *Ae. aegypti*–DENV system only exhibits a 1°C change for the wide range of host availability explored in Figure 5, so this result may not be a realistic estimate for actual populations.

The uncertainty in T_{opt} attributed to each mosquito trait varied substantially as vertebrate host population density was varied (Appendix S2: Figure S10). In every system, the adult mosquito lifespan (equivalently, the mortality rate) contributes greatly to the uncertainty in T_{opt} across a wide range of vertebrate host availability. In all but the *Cx. quinquefasciatus*–WNV system, eggs per female per day dominates the uncertainty when vertebrate host population density is low. Notably, the *Cx. quinquefasciatus*–WNV system exhibits the smallest change in T_{opt} as host availability is varied (Table 2). This suggests that differences in the thermal response of mosquito fecundity may be the cause of the observed differences in the relationship between T_{opt} and vertebrate host availability across the systems. Reducing uncertainty in the eggs per female per day trait would have an outsized impact on improving estimates of T_{opt} at lower levels of vertebrate host availability, except in the case of *Cx. quinquefasciatus*–WNV. Generally, the immature mosquito traits (immature development rate and probability of immature survival) contributed little to the uncertainty in T_{opt}. This result is consistent with the findings of our sensitivity analysis, which showed that these traits were not important determinants of the thermal response of $\mathcal{R}_0(T)$. When biting rate is not limited, the uncertainty results appear similar to the values obtained when vertebrate host population density is large.

TABLE 2 Maximum difference between T_{opt} when biting tolerance is unlimited ($T^{\text{RM}}_{\text{opt}}$) and limited ($T^{0}_{\text{opt}}$) in degrees Celsius in five transmission systems.

System	$T^{\text{RM}}_{\text{opt}}$	T^{0}_{opt}	$T^{\text{RM}}_{\text{opt}} - T^{0}_{\text{opt}}$
Aedes aegypti and DENV	26.8	27.95	−1.15
Aedes aegypti and ZIKV	26.8	28.4	−1.60
Aedes albopictus and DENV	28.35	33.9	−5.55
Anopheles gambiae and *Plasmodium falciparum*	26.4	21.35	5.05
Culex quinquefasciatus and WNV	25.45	25.75	−0.3

Abbreviations: DENV, Dengue virus; WNV, West Nile virus; ZIKV, Zika virus.

Thresholds for sustained transmission: Temperature and vertebrate host population density

The parasite population thermal niche is the range of temperatures at which the parasite population is expected to persist, that is, the temperatures at which $\mathcal{R}_0$ exceeds one. The critical thermal minimum, CT_{min}, and the critical thermal maximum, CT_{max}, bound the parasite population thermal niche. To illustrate how the parasite population thermal niche is shaped by vertebrate host availability, we plot the width of the parasite population thermal niche as a function of vertebrate host population density and biting tolerance (Figure 6).

Generally, vertebrate host species that are highly tolerant to mosquito biting and that have low population densities can support the widest parasite population thermal niche. The width of the parasite population thermal niche decreases as vertebrate host population density is increased, eventually shrinking to zero when population density surpasses the upper critical host community size, CH_{max}. But there is a change in this relationship when biting tolerance is low (around less than 100 bites per host per day). When biting tolerance is low, the width of the parasite population thermal niche is initially zero at low vertebrate host population densities. Then, as population density is increased past a threshold, CH_{min}, the width of the parasite population thermal niche increases rapidly.

Notably, this feature is absent from the Ross–Macdonald model, for which there is no lower critical host community size (Appendix S1: Section S3.2). For vertebrate host population densities exceeding roughly 1000 individuals per hectare, the width of the parasite population thermal niche is insensitive to biting tolerance. These observations suggest that vertebrate host populations with high biting tolerance and low abundances might best enable mosquito-borne parasites to persist in a changing thermal environment because these populations support transmission in the widest thermal band.

The *Cx. quinquefasciatus*–WNV system exhibits much wider variation in the width of the parasite population thermal niche than the other systems (Figure 6e). This is

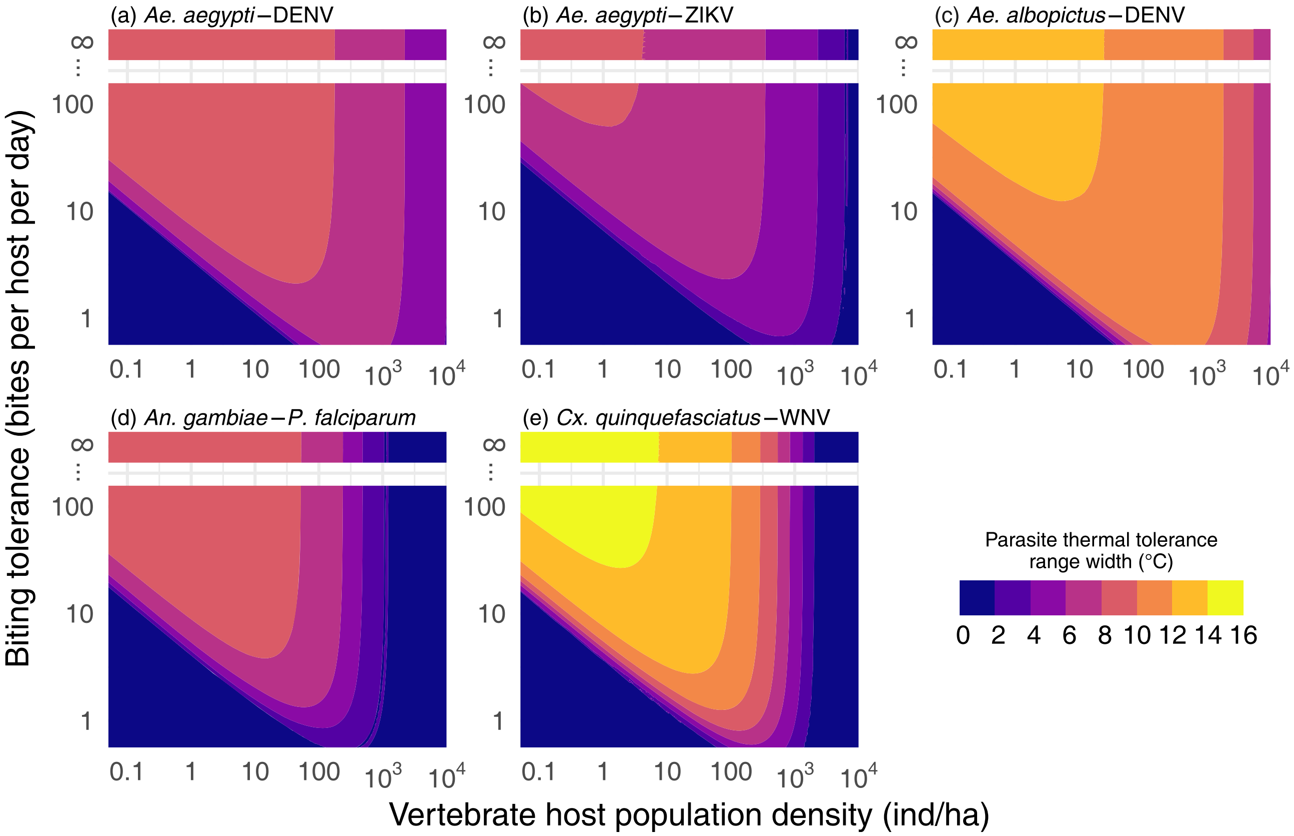

FIGURE 6 The parasite population thermal niche, the range of temperatures at which parasite transmission is expected to persist, is widest when biting tolerance is high and vertebrate host population density is low for the (a) *Ae. aegypti*–DENV, (b) *Ae. aegypti*–ZIKV, (c) *Ae. albopictus*–DENV, (d) *An. gambiae*–*P. falciparum*, and (e) *Cx. quinquefasciatus*–WNV systems. As vertebrate host population density approaches an upper threshold, the width of the parasite population thermal niche shrinks to zero. At low levels of biting tolerance, there is also a lower threshold for vertebrate host population density. Shown here are the median values of $\mathrm{CT}_{\mathrm{width}}$ with respect to the mosquito trait thermal performance curve posterior distributions. Vertebrate host population density and biting tolerance are both plotted on $\log_{10}$ scales. Biting tolerance is varied from 1 to 1000 bites per day, with an additional point at infinity to illustrate the case where biting tolerance is unlimited (the Ross–Macdonald model). Both biting tolerance and vertebrate host population density are varied on a $\log_{10}$ scale. All remaining parameters are given in Table 1 and Figure 3.

in contrast to the results for T_{opt}, where the *An. gambiae*–*P. falciparum* system displayed the greatest variation (Figure 5d). The wide variation in the width of the parasite population thermal niche for the *Cx. quinquefasciatus*–WNV system could be caused by the relatively low variance in $\mathrm{CT}_{\mathrm{min}}$ and $\mathrm{CT}_{\mathrm{max}}$ for this system (Appendix S2: Figure S8e).

We also considered how the critical thermal minimum ($\mathrm{CT}_{\mathrm{min}}$) and maximum ($\mathrm{CT}_{\mathrm{max}}$) were constrained by vertebrate host availability (Appendix S2: Figures S5 and S6). The parasite population thermal niche decreases in width as vertebrate host population density is increased while the critical minimum community size decreases along with biting tolerance (Appendix S2: Figure S7). The posterior distributions of $\mathrm{CT}_{\mathrm{min}}$, $\mathrm{CT}_{\mathrm{max}}$, and T_{opt} illustrate how the level of uncertainty changes due to vertebrate host availability (Appendix S2: Figure S8).

The contributions of each mosquito trait to uncertainty in $\mathrm{CT}_{\mathrm{min}}$, $\mathrm{CT}_{\mathrm{max}}$, and $\mathrm{CT}_{\mathrm{width}}$ change as host availability is increased (Appendix S2: Figures S11–S13). Visually, there was very little difference in any of these results between the cases of limited and unlimited biting tolerance. Uncertainty in $\mathrm{CT}_{\mathrm{min}}$ is primarily due to the parasite development rate and eggs per female per day, with adult mosquito lifespan growing in influence at higher levels of vertebrate host population density. For the *An. Gambiae*–*P. falciparum* system, uncertainty in $\mathrm{CT}_{\mathrm{min}}$ is driven almost entirely by the trait of eggs per female per day. In contrast, adult mosquito lifespan dominates $\mathrm{CT}_{\mathrm{max}}$ uncertainty, with eggs per female per day playing a larger role in only the *Ae. albopictus*–DENV system and *Cx. quinquefasciatus*–WNV system when vertebrate host availability is low. The uncertainty results for $\mathrm{CT}_{\mathrm{width}}$ are essentially a composite of the results for $\mathrm{CT}_{\mathrm{min}}$ and $\mathrm{CT}_{\mathrm{max}}$. In all, we see little influence of the

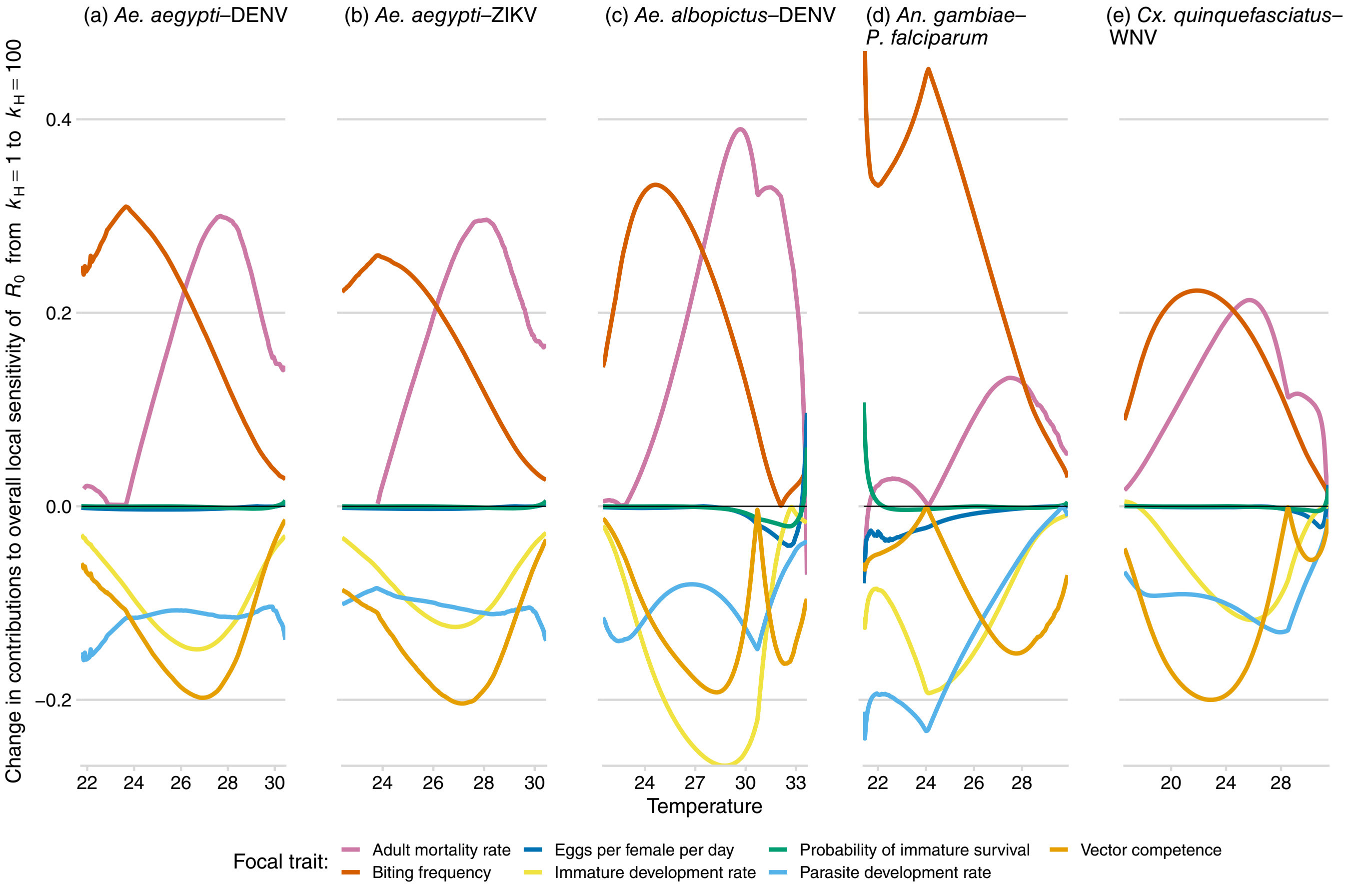

FIGURE 7 Change in contributions of temperature-dependent mosquito traits to overall temperature sensitivity of $\mathcal{R}_0$ as vertebrate host population density is increased from 1 to 100 individuals per hectare for the (a) *Ae. aegypti*–DENV, (b) *Ae. aegypti*–ZIKV, (c) *Ae. albopictus*–DENV, (d) *An. gambiae–P. falciparum*, and (e) *Cx. quinquefasciatus*–WNV systems. There is a fairly consistent pattern in the change in importance for four out of the five systems. But, unlike the others, the *Anopheles gambiae–Plasmodium falciparum* system displays significant changes in the contributions of biting frequency and parasite development rate at low temperatures and relatively small changes for adult mortality rate at warmer temperatures. This indicates that, through the incorporation of limited biting tolerance, a change in vertebrate host availability shifts the importance of certain temperature-dependent mosquito traits in determining the temperature dependence of $\mathcal{R}_0$. Shown here are the median values of $\overline{S}_p(T,\ 100,\ 10) - \overline{S}_p(T,\ 1,\ 10)$ as described by Equation (8).

immature development rate and probability of immature survival on either the thermal extrema or the width of the thermal niche.

DISCUSSION

Vertebrate host availability alters the transmission thermal optima of mosquito-borne parasites

The transmission thermal optimum, T_{opt}, is a commonly used measure of pathogen invasion risk (Mordecai et al., 2013, 2017, 2019; Nguyen et al., 2021; Shapiro et al., 2017; Shocket et al., 2020; Tesla et al., 2018; Villena et al., 2020). Past studies of mosquito-borne parasite transmission thermal optima have made an assumption, implicit in the use of the Ross–Macdonald model, that the biting tolerance of vertebrate hosts is unlimited. However, our findings suggest that ignoring the effect of host availability on mosquito contact may bias estimates of T_{opt} by as much as 5°C (Figure 5 and Appendix S2: Figure S3). Generally, incorporating biting tolerance had little impact on T_{opt} when vertebrate host population density or biting tolerance was assumed to be high (Figure 5). In most of the systems we considered, there was little difference between the values of T_{opt} obtained when biting tolerance was limited versus unlimited. But our results suggest that the magnitude of this effect depends strongly on the mosquito and parasite species in the transmission system, with the *An. gambiae–P. falciparum* system exhibiting a substantially larger change in T_{opt} when compared to the other systems considered here (Appendix S2: Figure S3d). Altogether, this result suggests that vertebrate host behavioral defenses that limit the rate of contact with mosquitoes can have an important effect on T_{opt}, especially when vertebrate host population density is low.

Distinct patterns in how the importance of the mosquito traits change due to increases in host availability might explain the observed differences in the thermal properties across the five transmission systems. For *An. gambiae–P. falciparum*, substantial shifts in T_{opt} as host availability is changed may be attributed to concomitant changes in the importance of certain traits (Figure 7d). Unlike the other systems, the *An. gambiae–P. falciparum* system exhibits large swings in the importance of biting frequency and parasite development for the temperature sensitivity of $\mathcal{R}_0(T)$ at cool temperatures (Figure 7).

At first glance, it seems that T_{opt}, a quantity describing the thermal performance of parasite transmission, should not exhibit any dependence on vertebrate host traits. However, animals, from birds to rodents to primates, commonly engage in behaviors that limit their exposure to mosquitoes, reducing the feeding success of these insects (Darbro & Harrington, 2007; Edman & Kale, 1971; Matherne et al., 2018; Samson et al., 2019; Walker & Edman, 1986). These behaviors should have the greatest impact on the contact dynamics between vertebrate hosts and mosquitoes when host density is already low, thereby substantially restricting the maximum rate at which mosquitoes make contact with their hosts (Figure 1a, red curve). This contrasts with the Ross–Macdonald model, which makes the underlying assumption that vertebrate hosts will tolerate any rate of biting and, therefore, that the contact rate will remain unaffected by decreases in the vertebrate host population density (Figure 1a, blue curve). By limiting the transmission rate of the parasite, vertebrate host defensive behaviors become key in determining the temperature dependence of mosquito-borne parasite transmission potential.

Given this relationship between biting tolerance and the determinants of mosquito-borne parasite transmission potential, a better understanding of the defensive behaviors of the vertebrate hosts of mosquito-borne zoonoses could improve risk projections of mosquito-borne disease. But data on the biting tolerance of animals are lacking. Although studies of animal defensive behaviors toward biting flies were once common (Cully Jr et al., 1991; Day & Edman, 1984; Edman et al., 1972, 1974; Edman & Kale, 1971; Edman & Scott, 1987; Hart, 1990, 1994; Klowden & Lea, 1979; Walker & Edman, 1985, 1986), this area of research has languished in the past two decades. Vertebrate host defensive behaviors and biting tolerance were not included in any of the models considered in two recent historical reviews of mathematical models of mosquito-borne pathogen transmission (Reiner Jr et al., 2013; Smith et al., 2012). Furthermore, to our knowledge, there has been no published research conducted on human tolerance thresholds to mosquito biting, though the existence of such thresholds is considered plausible (Read et al., 1994). Our results suggest that such studies would improve existing estimates of thermal optima for mosquito-borne parasite transmission to both humans and other animal reservoirs of mosquito-borne zoonoses in particular for human malaria transmission.

The results of our model cause us to propose two new hypotheses about the relationship between vertebrate host availability and mosquito-borne parasite transmission potential. The first hypothesis is that, in some systems, T_{opt} may vary with the biting tolerance of the vertebrate host. Holding the identity of the mosquito and parasite species constant, we should expect to measure dissimilar transmission thermal optima between a system with a biting-tolerant vertebrate host population versus one that is biting intolerant. Biting tolerance may be manipulated by restraining or anesthetizing hosts or otherwise minimizing their ability to defend against mosquito biting (Cully Jr et al., 1991; Lyimo et al., 2012). The second hypothesis is that, when the vertebrate host of a system is highly intolerant to biting, T_{opt} is sensitive to vertebrate host population density. In this case, changing the population density of the host population should measurably shift the temperature at which transmission is optimized. This hypothesis could be tested in mesocosm experiments that manipulate the population densities of host species that exhibit strong but imperfect defensive behavior, such as the wood rat or cotton rat (Edman & Scott, 1987), across a gradient of temperatures. Transmission potential can be evaluated using various measures that are related to $\mathcal{R}_0$, such as the initial growth rate in the number of infected animals (vertebrate hosts and mosquitoes) or by the prevalence of infection at the endpoint of the experiment. Our results suggest that detecting evidence for these hypotheses may be most likely in transmission systems with traits similar to the *An. gambiae–P. falciparum* system (Figure 5, Appendix S2: Figures S2 and S3). Desirable properties for the mosquito and pathogen of this experimental system might include adult mosquito survival at relatively cold temperatures, reproduction only at warmer temperatures, and vector competence across a wide thermal range as these properties differentiate the *An. gambiae–P. falciparum* system from the other systems considered in this study (Figure 3). Exploring these hypotheses would improve our understanding of the role of the vertebrate host in the transmission of mosquito-borne parasites.

Key traits of the vertebrate host that modulate the effects of temperature and other environmental factors on transmission potential were not considered in other studies, which largely explored mosquito-borne parasite transmission thermal optima using quantities like the entomological inoculation rate, vectorial capacity, or a normalized form of the basic reproduction number to measure transmission potential (Childs et al., 2019; Mordecai et al., 2013, 2017, 2019; Ngonghala et al., 2021; Nova et al., 2021; Ryan et al., 2019; Shapiro et al., 2017; Shocket et al., 2020; Tesla et al., 2018). Using such quantities allows one to avoid the estimation of host parameters and mosquito abundance through the assumption of a fixed ratio of vector and host abundances. But the assumption of a fixed vector–host ratio leads to an unrealistic implication—that any change in mosquito abundance (say, due to temperature or other abiotic factors) is met with a proportional change in host abundance. Even the most fast-lived hosts have population turnover times significantly longer than that of mosquitoes. Future modeling studies might consider incorporating realistic covariation of vector and host population sizes (Romeo-Aznar et al., 2018; Wonham et al., 2006).

Our results suggest that quantities like the transmission thermal optimum may, in fact, be sensitive to vertebrate host population density. If the maximum change in T_{opt} (Table 2) for a given pair of mosquito and parasite species is deemed to be sufficiently small (as may be the case for *Cx. quinquefasciatus*–WNV), then ignoring host traits is justified as they are unlikely to substantially impact the relationship between temperature and peak transmission. On the other hand, in the case of the *An. gambiae*–*P. falciparum* system, it may be more suitable to use ecologically realistic models, like the one presented here, that can estimate a range of possible T_{opt} values determined by host availability, as simplifying assumptions may bias estimates by over 5°C. The maximum change estimate of T_{opt} could be used to identify mosquito–parasite transmission systems where better data on the traits of vertebrate hosts could improve estimates of T_{opt} going forward. Uncertainty analyses suggest that additional data on the thermal response of adult mosquito lifespan, vector competence, and eggs per female per day would best resolve the uncertainty in T_{opt} estimates.

Paired with projections of temperature shifts due to global climate change, thermal optima estimates could eventually help decision-makers prepare for and potentially prevent the spread of mosquito-borne pathogens. Changes in thermal optima, even on the order of single degrees, can lead to substantial adjustments to maps of future mosquito-borne disease risk (Mordecai et al., 2019). However, the transmission thermal optimum is not the sole determinant of mosquito-borne parasite risk. Importantly, $\mathcal{R}_0$ may be maximized at a particular temperature but still not exceed the threshold for an outbreak. Furthermore, the $\mathcal{R}_0$ TPC may be flat near its maximum, meaning that deviations in temperature away from T_{opt} result in only slight changes in $\mathcal{R}_0$. For these reasons, considering the thermal niche of the parasite population is also essential.

Vertebrate host availability shapes the thresholds for sustained mosquito-borne parasite transmission

Incorporating vertebrate host traits into models enabled us to directly calculate the basic reproduction number, $\mathcal{R}_0$, and hence the parasite population thermal niche. We showed that vertebrate host availability affected both the width of the parasite population thermal niche and its position relative to the mosquito population thermal niche (Figure 6 and Appendix S2: Figure S6). Consistent with our findings related to T_{opt}, the critical thermal minimum and maximum, CT_{min} and CT_{max}, were not independent of vertebrate host population density (Appendix S2: Figures S5 and S6). Above a threshold level of vertebrate host population density parasite transmission did not persist at any temperature (Figure 6). A lower vertebrate host critical community size exists when the vertebrate host exhibits limited biting tolerance, marking a substantial difference from past works that used the Ross–Macdonald contact model.

While the relationship between parasite thermal tolerance range width and host availability is similar across the systems, we note that the *Cx. quinquefasciatus*–WNV system exhibits much larger increases in width when biting tolerance is high and population density is low. Unlike with *An. gambiae*–*P. falciparum*, we cannot clearly differentiate *Cx. quinquefasciatus*–WNV from the other systems by examining how host availability shifts the importance of traits (Figure 7e). However, our uncertainty analysis suggests that the thermal response of vector competence is a more important trait for determining CT_{min} and, thus, CT_{width} for this systems.

The links identified between the parasite population thermal niche and the vertebrate host population thresholds may have important implications for the prediction and prevention of the spread of mosquito-borne pathogens and for the elimination of endemic or enzootic mosquito-borne pathogens. Like T_{opt}, the parasite population thermal niche can be used to determine which regions could be at future risk of mosquito-borne parasite invasion and establishment due to global climate change. But unlike T_{opt}, the parasite population thermal niche takes into account both the absolute and relative aspects of $\mathcal{R}_0$. Whereas T_{opt} includes no information about the probability of an outbreak or whether transmission is expected to be sustained, the parasite population thermal niche only includes the temperatures at which outbreaks and sustained transmission are expected. Our results show that vertebrate host behaviors and traits may indirectly interact with the effects of temperature on mosquito and parasite traits to restrict the parasite population thermal niche. For example, if vertebrate host biting tolerance is ignored, the width of the parasite population thermal niche may be overestimated, particularly at low levels of vertebrate host population density (Figure 6).

The connections between the parasite population thermal niche and vertebrate host population densities suggest two empirically testable hypotheses regarding vector–host contact dynamics and mosquito-borne parasite transmission. First, our results suggest that when biting tolerance is low, the parasite population thermal niche should be broad only in a narrow range of high vertebrate host population densities. This suggests that in species with low tolerance to mosquito biting, we should only expect to find sustained transmission of mosquito-borne parasites in relatively dense populations. Mesocosm experiments that measure the degree to which mosquitoes transmit parasites to populations of defensive animals, like rodents (Edman & Scott, 1987), across a range of host population densities and ambient temperatures could help to determine whether this finding represents a real phenomenon. On the other hand, for biting-tolerant animals, there should be relatively little change in the range of temperatures at which transmission will be sustained when population density is varied across a wide range of values.

Our findings also lead to a second hypothesis: If hosts are too abundant relative to the vector population, the parasite population is not expected to become established in the long term. This is in direct contrast to theories of critical thresholds for directly transmitted parasites where there are only minimum community sizes below which persistent parasite transmission does not occur (Nunn & Altizer, 2006). While the existence of a maximum population size for transmission may appear counterintuitive, it is a well-known property of the familiar Ross–Macdonald model (Keeling & Rohani, 2008) and the main idea underlying the concept of zooprophylaxis (Kilpatrick & Randolph, 2012), the idea that living near other animals (often livestock) provides a defense against mosquito-borne disease as infected mosquitoes are diverted toward these animals and away from humans. This threshold has a possible phenomenological explanation: When there is a sufficiently high density of vertebrate hosts and only a few infected individuals, the probability that a susceptible mosquito makes contact with an infected vertebrate host is vanishingly small. However, while studies have identified a strong correlation between population density and mosquito-borne disease incidence, we were only able to find studies showing that the incidence of mosquito-borne disease increases with population density (Li et al., 2021; Liu et al., 2020; Rogers et al., 2014).

A better understanding of the natural covariation of vertebrate host traits would allow us to better contextualize these results. Should we expect vertebrates living in high-density populations to have higher or lower biting tolerance levels than those living in low-density populations? Negative correlations between body mass and biting tolerance (Edman & Scott, 1987) and body mass and population density (De Leo & Dobson, 1996; Han et al., 2015) may help to explain which vertebrate host species are most likely to support sustained mosquito-borne parasite transmission across a wide range of temperatures. This correlation, together with our results, suggests that small-bodied animals, despite being more actively defensive against mosquitoes (Edman & Scott, 1987), may induce a wide parasite population thermal niche because of their high population densities. Similarly, large-bodied animals, which tend to have higher biting tolerances and lower population densities, may also support a wide parasite population thermal niche. These trade-offs between the biting tolerances and population densities of vertebrate hosts, mediated through body mass, may tend to place vertebrates in the regions of parameter space where transmission is sustained at the widest possible range of temperatures.

Finally, these results are relevant to mosquito-borne parasite invasion and maintenance in human populations. Recent evidence suggests that dengue virus transmission depends on the availability of susceptible humans (Li et al., 2021; Liu et al., 2020; Nova et al., 2021). But there has been little research into how human behavior changes due to biting pressure from mosquitoes. Our results suggest that determining the existence of biting tolerance thresholds for human populations could improve estimates of mosquito-borne parasite risk in human populations under future climate warming scenarios. Because reducing biting tolerance greatly shrinks the width of the parasite population thermal niche in small populations, providing people in sparsely populated communities with tools that help to defend against mosquito biting (such as bed nets or *permethrin*-treated clothing) could have an outsized effect on limiting the sustained transmission of mosquito-borne pathogens.

Areas for further research

We assumed that temperature was constant and time independent to preserve the autonomy of our model.

In the field, mosquitoes and their parasites experience daily and seasonal changes in temperature that affect transmission-related traits (Alto et al., 2018; McGregor et al., 2021; Meyer et al., 1990; Reisen et al., 1986). These processes will be most important in temperate regions where seasonal and daily shifts in temperature can be substantial. However, studies looking at how changes in daily temperature range affect the transmission rate of arboviruses in mosquitoes have shown mixed results (Alto et al., 2018; Lambrechts et al., 2011; McGregor et al., 2021; Paaijmans et al., 2009, 2010). It is possible to include seasonal and daily oscillations of temperature into compartmental models and to determine $\mathcal{R}_0$ in such periodic environments (Bacaër, 2007; Wang & Zhao, 2008). Finally, because temperature is so closely linked to mosquito fitness, mosquitoes may adapt to survive in new temperature regimes, thereby fundamentally changing the thermal response of their life history traits (Couper et al., 2021, 2023; Ruybal et al., 2016; Sternberg & Thomas, 2014).

Additionally, we made several simplifying assumptions about mosquito biology that might affect the generality of our results. The temperature experienced by mosquitoes in larval stages can have carry-over effects on their phenotype as adults: Higher temperatures are associated with faster development times, lower adult body sizes, and lower egg production and may also impact adult fecundity, pathogen susceptibility, mortality, and mosquito biting rate (Evans et al., 2018, 2021; Huxley et al., 2021, 2022; Rueda et al., 1990; Shapiro et al., 2016). Carry-over effects could be accounted for in compartmental models by adding an age variable for mosquitoes (necessitating the use of a system of partial differential equations). Including such carry-over effects would likely change the uncertainty and sensitivity results presented here that suggest immature mosquito traits are not important determinants of model results.

The assumption that mosquitoes seek a single blood meal each gonotrophic cycle is also unrealistic. Some mosquito species regularly engage in multiple blood feeding (Amerasinghe & Amerasinghe, 1999; Anderson & Brust, 1995; Silver, 2008a), whereas others will engage in multiple blood feeding when their feeding is disrupted by host behavioral defenses (Anderson & Brust, 1997; Anderson & Roitberg, 1999; Darbro & Harrington, 2007; Yan et al., 2021). Recent efforts have been made to incorporate the dynamics of multiple blood feeding into dynamic models (Ghakanyuy et al., 2022). Multiple blood feeding may also be more likely to occur when a mosquito is infected with a parasite (Koella et al., 1998). Our sensitivity analysis indicated that biting rate is an important determinant of the thermal response of $\mathcal{R}_0$. However, our uncertainty analyses suggest that, relative to other traits, resolving uncertainty in the thermal response data for biting rate would not improve estimates of $\mathcal{R}_0$, T_{opt}, or the parasite population thermal niche.

The lack of knowledge of absolute mosquito density also limits the interpretability of our results. But accurate estimates of adult mosquito population density are difficult to obtain, leading researchers to rely instead on relative measures of mosquito abundance, such as catches per trap night (Silver, 2008b). In addition, the common assumption that mosquito density is independent of host density may be unrealistic, and models can be modified to consider when these densities covary (Romeo-Aznar et al., 2018). Our results may be robust to a wide range of mosquito population densities because mosquito population density only enters into the equation of $\mathcal{R}_0$ in the form of the vector-to-host ratio. A wide range of vector-to-host ratio values was explored by varying the vertebrate host population density. For the same reason, the assumption of a constant immature mosquito carrying capacity may not have a significant impact on our results as in our models this quantity is proportional to the adult mosquito abundance. A straightforward extension to this study could evaluate the effect of changing the larval habitat availability (i.e., carrying capacity, K_L in this model) to correlate with vertebrate host population density, which may be particularly applicable to urban-dwelling, container-breeding mosquitoes like *Ae. aegypti*.

Similarly, assumptions about how vertebrate hosts respond to biting from mosquitoes are essential to the models reported here. The limited evidence available suggests that there can be substantial heterogeneity in biting tolerance both within and across species and that defensiveness may depend on host age, size, or infection status (Day & Edman, 1984; Edman et al., 1974; Edman & Spielman, 1988; Read et al., 1994). We assumed that vertebrate host behavioral defenses imposed an upper limit on the contact rate experienced by vertebrate hosts that was independent of the number of mosquitoes and their biting rate. But persistent mosquitoes may be able to overcome any defensive behaviors engaged in by a host, and mosquitoes have other ways of circumventing behavioral defenses such as attacking at night when hosts are least active (Walker & Edman, 1985). On the other hand, host defensive behaviors can increase the mortality rate of mosquitoes (Darbro & Harrington, 2007; Kelly, 2001; Silver, 2008a). Furthermore, host defensive behaviors may in fact lead to increased overall contact rates due to interrupted blood feeding (Walker & Edman, 1985). A more realistic model of vertebrate host biting tolerance would take into account that behavioral defenses likely only lead to relative reductions in contact rates. Finally, it is unclear to what extent the findings here would apply to other interventions that reduce the overall contact rate of hosts with mosquitoes but not necessarily the overall availability of hosts, such as the use of bed nets.

CONCLUSION

This study reinforces the importance of vertebrate host traits for mosquito-borne pathogen transmission. Incorporating vertebrate host availability (and vertebrate host traits in general) along with more realistic contact dynamics into our model allowed us to derive absolute measures of sustained transmission, like the parasite population thermal niche, instead of solely relative ones, like the transmission thermal optimum. Vertebrate host biting tolerance—and behavioral defenses against biting more generally—likely play an important role in transmission, determining both the temperature at which transmission peaks and the range of temperatures at which transmission can be sustained. Thus, increasing our knowledge of vertebrate host behavioral defenses against mosquito biting could improve our ability to predict which species are most likely to serve as reservoirs of mosquito-borne parasites. Understanding what drives differences in the relationship between the thermal properties of transmission and vertebrate host availability among different transmission systems may best be pursued by resolving uncertainty in the thermal response of three key traits: adult mosquito lifespan, eggs per female per day, and the probability of surviving the extrinsic incubation period. These results are also dependent on population density—while biting tolerance is a critical determinant of sustained transmission for small populations, it matters much less in highly dense populations. This dependence suggests that in regions where global climate change is projected to increase mosquito-borne disease risk, small human communities could receive disproportionate benefits from interventions targeting mosquito biting compared to large communities.

AUTHOR CONTRIBUTIONS

Kyle J.-M. Dahlin: conceptualization, methodology, software, formal analysis, data curation, writing—original draft, writing—review and editing, visualization. **Suzanne M. O'Regan**: conceptualization, methodology, writing—review and editing, supervision, funding acquisition. **Barbara A. Han**: conceptualization, writing—review and editing, funding acquisition. **John Paul Schmidt**: conceptualization, methodology, writing—review and editing, funding acquisition. **John M. Drake**: conceptualization, writing—review and editing, supervision, project administration.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation Ecology and Evolution of Infectious Diseases program (DEB 1717282 to BAH, SO, JPS, JD). The authors would also like to thank Eric Marty for creating Figure 2 and Soham Sajekar for assistance with visualizations.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data and code (Dahlin et al., 2024) are available in Zenodo at https://doi.org/10.5281/zenodo.10569710.

ORCID

Kyle J.-M. Dahlin https://orcid.org/0000-0002-1116-8074
Barbara A. Han https://orcid.org/0000-0002-9948-3078

REFERENCES

Agusto, F. B., A. B. Gumel, and P. E. Parham. 2015. "Qualitative Assessment of the Role of Temperature Variations on Malaria Transmission Dynamics." *Journal of Biological Systems* 23: 1550030.

Alto, B. W., K. Wiggins, B. Eastmond, S. Ortiz, K. Zirbel, and L. P. Lounibos. 2018. "Diurnal Temperature Range and Chikungunya Virus Infection in Invasive Mosquito Vectors." *Journal of Medical Entomology* 55: 217–224.

Amerasinghe, P. H., and F. P. Amerasinghe. 1999. "Multiple Host Feeding in Field Populations of Anopheles Culicifacies and An. Subpictus in Sri Lanka." *Medical and Veterinary Entomology* 13: 124–131.

Anderson, R. A., and R. A. Brust. 1995. "Field Evidence for Multiple Host Contacts during Blood Feeding by *Culex tarsalis*, *Cx. restuans*, and *Cx. nigripalpus* (Diptera: Culicidae)." *Journal of Medical Entomology* 32: 705–710.

Anderson, R. A., and R. A. Brust. 1997. "Interrupted Blood Feeding by *Culex* (Diptera:Culicidae) in Relation to Individual Host Tolerance to Mosquito Attack." *Journal of Medical Entomology* 34: 95–101.

Anderson, R. A., and B. D. Roitberg. 1999. "Modelling Trade-Offs between Mortality and Fitness Associated with Persistent Blood Feeding by Mosquitoes." *Ecology Letters* 2: 98–105.

Angilletta, M. J. 2006. "Estimating and Comparing Thermal Performance Curves." *Journal of Thermal Biology* 31: 541–45.

Aytekin, S., A. M. Aytekin, and B. Alten. 2009. "Effect of Different Larval Rearing Temperatures on the Productivity (R_o) and Morphology of the Malaria Vector *Anopheles superpictus* Grassi (Diptera: Culicidae) Using Geometric Morphometrics." *Journal of Vector Ecology* 34: 32–42.

Bacaër, N. 2007. "Approximation of the Basic Reproduction Number R_0 for Vector-Borne Diseases with a Periodic Vector Population." *Bulletin of Mathematical Biology* 69: 1067–91.

Beier, J. C. 1998. "Malaria Parasite Development in Mosquitoes." *Annual Review of Entomology* 43: 519–543.

Bhatt, S., P. W. Gething, O. J. Brady, J. P. Messina, A. W. Farlow, C. L. Moyes, J. M. Drake, et al. 2013. "The Global Distribution and Burden of Dengue." *Nature* 496: 504–7.

Brady, O. J., N. Golding, D. M. Pigott, M. U. G. Kraemer, J. P. Messina, R. C. Reiner, Jr., T. W. Scott, D. L. Smith, P. W. Gething, and S. I. Hay. 2014. "Global Temperature Constraints on *Aedes aegypti* and *Ae. Albopictus* Persistence and Competence for Dengue Virus Transmission." *Parasites & Vectors* 7: 338.

Chamberlain, R. W., and W. D. Sudia. 1961. "Mechanism of Transmission of Viruses by Mosquitoes." *Annual Review of Entomology* 6: 371–390.

Childs, M. L., N. Nova, J. Colvin, and E. A. Mordecai. 2019. "Mosquito and Primate Ecology Predict Human Risk of Yellow Fever Virus Spillover in Brazil." *Philosophical Transactions of The Royal Society of London. Series B, Biological Sciences* 374: 20180335.

Chitnis, N., J. M. Cushing, and J. M. Hyman. 2006. "Bifurcation Analysis of a Mathematical Model for Malaria Transmission." *SIAM Journal on Applied Mathematics* 67: 24–45.

Chitnis, N., J. M. Hyman, and C. A. Manore. 2013. "Modelling Vertical Transmission in Vector-Borne Diseases with Applications to Rift Valley Fever." *Journal of Biological Dynamics* 7: 11–40.

Christiansen-Jucht, C. D., P. E. Parham, A. Saddler, J. C. Koella, and M.-G. Basáñez. 2015. "Larval and Adult Environmental Temperatures Influence the Adult Reproductive Traits of *Anopheles gambiae* s.s." *Parasites & Vectors* 8: 1–12.

Ciota, A. T., and A. C. Keyel. 2019. "The Role of Temperature in Transmission of Zoonotic Arboviruses." *Viruses* 11: 1013.

Cohen, J. M., E. L. Sauer, O. Santiago, S. Spencer, and J. R. Rohr. 2020. "Divergent Impacts of Warming Weather on Wildlife Disease Risk across Climates." *Science* 370: eabb1702.

Couper, L. I., J. E. Farner, J. M. Caldwell, M. L. Childs, M. J. Harris, D. G. Kirk, N. Nova, et al. 2021. "How Will Mosquitoes Adapt to Climate Warming?" *eLife* 10: e69630.

Couper, L. I., J. E. Farner, K. P. Lyberger, A. S. Lee, and E. A. Mordecai. 2023. "Evidence of Thermal Adaptation in a Widely Distributed Mosquito Species." https://doi.org/10.1101/2023.03.02.530886.

Cully, J. F., Jr., J. P. Grieco, and D. Kissel. 1991. "Defensive Behavior of Eastern Chipmunks against *Aedes triseriatus* (Diptera: Culicidae)." *Journal of Medical Entomology* 28: 410–16.

Dahlin, K., S. O'Regan, B. Han, J. P. Schmidt, and J. Drake. 2024. "Data and Code for 'Impacts of Host Availability and Temperature on Mosquito-Borne Parasite Transmission'." Zenodo. https://doi.org/10.5281/zenodo.10569710.

Darbro, J. M., and L. C. Harrington. 2007. "Avian Defensive Behavior and Blood-Feeding Success of the West Nile Vector Mosquito, *Culex pipiens*." *Behavioral Ecology* 18: 750–57.

Daszak, P., A. A. Cunningham, and A. D. Hyatt. 2000. "Emerging Infectious Diseases of Wildlife–Threats to Biodiversity and Human Health." *Science* 287: 443–49.

Davies, C. R. 1990. "Interrupted Feeding of Blood-Sucking Insects: Causes and Effects." *Parasitology Today* 6: 19–22.

Day, J. F., and J. D. Edman. 1984. "Mosquito Engorgement on Normally Defensive Hosts Depends on Host Activity Patterns." *Journal of Medical Entomology* 21: 732–740.

De Leo, G. A., and A. P. Dobson. 1996. "Allometry and Simple Epidemic Models for Microparasites." *Nature* 379: 720–22.

Diekmann, O., J. A. Heesterbeek, and J. A. Metz. 1990. "On the Definition and the Computation of the Basic Reproduction Ratio R_0 in Models for Infectious Diseases in Heterogeneous Populations." *Journal of Mathematical Biology* 28: 365–382.

Edman, J. D. 1989. "Are Mosquitoes Gourmet or Gourmand?" *Journal of the American Mosquito Control Association* 5: 487–499.

Edman, J. D., and H. W. Kale. 1971. "Host Behavior: Its Influence on the Feeding Success of Mosquitoes." *Annals of the Entomological Society of America* 64: 513–16.

Edman, J. D., and T. W. Scott. 1987. "Host Defensive Behaviour and the Feeding Success of Mosquitoes." *International Journal of Tropical Insect Science* 8: 617–622.

Edman, J. D., and A. Spielman. 1988. "Blood-Feeding by Vectors: Physiology, Ecology, Behavior, and Vertebrate Defense." In *The Arboviruses: Epidemiology and Ecology*, Vol. I, edited by T. P. Monath, 153–191. Boca Raton, FL: CRC Press.

Edman, J. D., L. A. Webber, and H. W. Kale, 2nd. 1972. "Effect of Mosquito Density on the Interrelationship of Host Behavior and Mosquito Feeding Success." *The American Journal of Tropical Medicine and Hygiene* 21: 487–491.

Edman, J. D., L. A. Webber, and A. A. Schmid. 1974. "Effect of Host Defenses on the Feeding Pattern of Culex Nigripalpus when Offered a Choice of Blood Sources." *The Journal of Parasitology* 60: 874–883.

Evans, M. V., J. M. Drake, L. Jones, and C. C. Murdock. 2021. "Assessing Temperature-Dependent Competition between Two Invasive Mosquito Species." *Ecological Applications* 31: e02334.

Evans, M. V., J. C. Shiau, N. Solano, M. A. Brindley, J. M. Drake, and C. C. Murdock. 2018. "Carry-Over Effects of Urban Larval Environments on the Transmission Potential of Dengue-2 Virus." *Parasites & Vectors* 11: 426.

Faust, C., and A. P. Dobson. 2015. "Primate Malarias: Diversity, Distribution and Insights for Zoonotic *Plasmodium*." *One Health (Amsterdam, Netherlands)* 1: 66–75.

Franklinos, L. H. V., K. E. Jones, D. W. Redding, and I. Abubakar. 2019. "The Effect of Global Change on Mosquito-Borne Disease." *The Lancet Infectious Diseases* 19: e302–e312.

Gething, P. W., T. P. Van Boeckel, D. L. Smith, C. A. Guerra, A. P. Patil, R. W. Snow, and S. I. Hay. 2011. "Modelling the Global Constraints of Temperature on Transmission of *Plasmodium falciparum* and *P. vivax*." *Parasites & Vectors* 4: 92.

Ghakanyuy, B. M., M. I. Teboh-Ewungkem, K. A. Schneider, and G. A. Ngwa. 2022. "Investigating the Impact of Multiple Feeding Attempts on Mosquito Dynamics Via Mathematical Models." *Mathematical Biosciences* 350: 108832.

Gibbons, R. V., and D. W. Vaughn. 2002. "Dengue: An Escalating Problem." *BMJ* 324: 1563–66.

Graumans, W., E. Jacobs, T. Bousema, and P. Sinnis. 2020. "When Is a *Plasmodium*-Infected Mosquito an Infectious Mosquito?" *Trends in Parasitology* 36: 705–716.

Hamer, G. L., U. D. Kitron, T. L. Goldberg, J. D. Brawn, S. R. Loss, M. O. Ruiz, D. B. Hayes, and E. D. Walker. 2009. "Host Selection by *Culex pipiens* Mosquitoes and West Nile Virus Amplification." *The American Journal of Tropical Medicine and Hygiene* 80: 268–278.

Han, B. A., A. W. Park, A. E. Jolles, and S. Altizer. 2015. "Infectious Disease Transmission and Behavioural Allometry in Wild Mammals." *The Journal of Animal Ecology* 84: 637–646.

Hart, B. L. 1990. “Behavioral Adaptations to Pathogens and Parasites: Five Strategies.” *Neuroscience and Biobehavioral Reviews* 14: 273–294.

Hart, B. L. 1994. “Behavioural Defense against Parasites: Interaction with Parasite Invasiveness.” *Parasitology* 109(Suppl): S139–S151.

Haufe, W. O. 1987. “Host-Parasite Interaction of Blood-Feeding Dipterans in Health and Productivity of Mammals.” *International Journal for Parasitology* 17: 607–614.

Hopkins, S. R., I. J. Jones, J. C. Buck, C. LeBoa, L. H. Kwong, K. Jacobsen, C. Rickards, et al. 2022. “Environmental Persistence of the World’s Most Burdensome Infectious and Parasitic Diseases.” *Frontiers in Public Health* 10: 892366.

Huey, R. B., and J. G. Kingsolver. 1989. “Evolution of Thermal Sensitivity of Ectotherm Performance.” *Trends in Ecology & Evolution* 4: 131–35.

Huey, R. B., and R. D. Stevenson. 1979. “Integrating Thermal Physiology and Ecology of Ectotherms: A Discussion of Approaches.” *American Zoologist* 19: 357–366.

Huxley, P. J., K. A. Murray, S. Pawar, and L. J. Cator. 2021. “The Effect of Resource Limitation on the Temperature Dependence of Mosquito Population Fitness.” *Proceedings Biological Sciences/The Royal Society* 288: 20203217.

Huxley, P. J., K. A. Murray, S. Pawar, and L. J. Cator. 2022. “Competition and Resource Depletion Shape the Thermal Response of Population Fitness in Aedes Aegypti.” *Communications Biology* 5: 66.

Johnson, L. R., T. Ben-Horin, K. D. Lafferty, A. McNally, E. Mordecai, K. P. Paaijmans, S. Pawar, and S. J. Ryan. 2015. “Understanding Uncertainty in Temperature Effects on Vector-Borne Disease: A Bayesian Approach.” *Ecology* 96: 203–213.

Jones, K. E., N. G. Patel, M. A. Levy, A. Storeygard, D. Balk, J. L. Gittleman, and P. Daszak. 2008. “Global Trends in Emerging Infectious Diseases.” *Nature* 451: 990–93.

Keeling, M. J., and P. Rohani. 2008. *Modeling Infectious Diseases in Humans and Animals*. Princeton, NJ: Princeton University Press.

Kelly, D. W. 2001. “Why Are Some People Bitten More than Others?” *Trends Parasitology* 17: 578–581.

Kilpatrick, A. M. 2011. “Globalization, Land Use, and the Invasion of West Nile Virus.” *Science* 334: 323–27.

Kilpatrick, A. M., P. Daszak, M. J. Jones, P. P. Marra, and L. D. Kramer. 2006. “Host Heterogeneity Dominates West Nile Virus Transmission.” *Proceedings Biological Sciences/The Royal Society* 273: 2327–33.

Kilpatrick, A. M., and S. E. Randolph. 2012. “Drivers, Dynamics, and Control of Emerging Vector-Borne Zoonotic Diseases.” *The Lancet* 380: 1946–55.

Klowden, M. J., and A. O. Lea. 1979. “Effect of Defensive Host Behavior on the Blood Meal Size and Feeding Success of Natural Populations of Mosquitoes (Diptera: Culicidae).” *Journal of Medical Entomology* 15: 514–17.

Koella, J. C., F. L. Sørensen, and R. A. Anderson. 1998. “The Malaria Parasite, *Plasmodium falciparum*, Increases the Frequency of Multiple Feeding of its Mosquito Vector, *Anopheles gambiae*.” *Proceedings Biological Sciences/The Royal Society* 265: 763–68.

Kramer, L. D., A. T. Ciota, and A. M. Kilpatrick. 2019. “Introduction, Spread, and Establishment of West Nile Virus in the Americas.” *Journal of Medical Entomology* 56: 1448–55.

Lambrechts, L., K. P. Paaijmans, T. Fansiri, L. B. Carrington, L. D. Kramer, M. B. Thomas, and T. W. Scott. 2011. “Impact of Daily Temperature Fluctuations on Dengue Virus Transmission by *Aedes aegypti*.” *Proceedings of the National Academy of Sciences of the United States of America* 108: 7460–65.

Laporta, G. Z., Y.-M. Linton, R. C. Wilkerson, E. S. Bergo, S. S. Nagaki, D. C. Sant’Ana, and M. A. M. Sallum. 2015. “Malaria Vectors in South America: Current and Future Scenarios.” *Parasites & Vectors* 8: 426.

Li, C., X. Wu, S. Sheridan, J. Lee, X. Wang, J. Yin, and J. Han. 2021. “Interaction of Climate and Socio-Ecological Environment Drives the Dengue Outbreak in Epidemic Region of China.” *PLoS Neglected Tropical Diseases* 15: e0009761.

Liu, K., X. Hou, Z. Ren, R. Lowe, Y. Wang, R. Li, X. Liu, et al. 2020. “Climate Factors and the East Asian Summer Monsoon May Drive Large Outbreaks of Dengue in China.” *Environmental Research* 183: 109190.

Lyimo, I. N., D. T. Haydon, K. F. Mbina, A. A. Daraja, E. M. Mbehela, R. Reeve, and H. M. Ferguson. 2012. “The Fitness of African Malaria Vectors in the Presence and Limitation of Host Behaviour.” *Malaria Journal* 11: 425.

Manore, C. A., K. S. Hickmann, S. Xu, H. J. Wearing, and J. M. Hyman. 2014. “Comparing Dengue and Chikungunya Emergence and Endemic Transmission in *A. aegypti* and *A. albopictus*.” *Journal of Theoretical Biology* 356: 174–191.

Manore, C. A., R. S. Ostfeld, F. B. Agusto, H. Gaff, and S. L. LaDeau. 2017. “Defining the Risk of Zika and Chikungunya Virus Transmission in Human Population Centers of the Eastern United States.” *PLoS Neglected Tropical Diseases* 11: e0005255.

Matherne, M. E., K. Cockerill, Y. Zhou, M. Bellamkonda, and D. L. Hu. 2018. “Mammals Repel Mosquitoes with their Tails.” *The Journal of Experimental Biology* 221: 178905.

McGregor, B. L., J. L. Kenney, and C. R. Connelly. 2021. “The Effect of Fluctuating Incubation Temperatures on West Nile Virus Infection in *Culex* Mosquitoes.” *Viruses* 13: 1822.

Messina, J. P., O. J. Brady, N. Golding, M. U. G. Kraemer, G. R. W. Wint, S. E. Ray, D. M. Pigott, et al. 2019. “The Current and Future Global Distribution and Population at Risk of Dengue.” *Nature Microbiology* 4: 1508–15.

Messina, J. P., M. U. Kraemer, O. J. Brady, D. M. Pigott, F. M. Shearer, D. J. Weiss, N. Golding, et al. 2016. “Mapping Global Environmental Suitability for Zika Virus.” *eLife* 5: e15272.

Meyer, R. P., J. L. Hardy, and W. K. Reisen. 1990. “Diel Changes in Adult Mosquito Microhabitat Temperatures and their Relationship to the Extrinsic Incubation of Arboviruses in Mosquitoes in Kern County, California.” *Journal of Medical Entomology* 27: 607–614.

Mordecai, E. A., J. M. Caldwell, M. K. Grossman, C. A. Lippi, L. R. Johnson, M. Neira, J. R. Rohr, et al. 2019. “Thermal Biology of Mosquito-Borne Disease.” *Ecology Letters* 22: 1690–1708.

Mordecai, E. A., J. M. Cohen, M. V. Evans, P. Gudapati, L. R. Johnson, C. A. Lippi, K. Miazgowicz, et al. 2017. “Detecting the Impact of Temperature on Transmission of Zika, Dengue, and Chikungunya Using Mechanistic Models.” *PLoS Neglected Tropical Diseases* 11: e0005568.

Mordecai, E. A., K. P. Paaijmans, L. R. Johnson, C. Balzer, T. Ben-Horin, E. de Moor, A. McNally, et al. 2013.

"Optimal Temperature for Malaria Transmission Is Dramatically lower than Previously Predicted." *Ecology Letters* 16: 22–30.

Ngonghala, C. N., S. J. Ryan, B. Tesla, L. R. Demakovsky, E. A. Mordecai, C. C. Murdock, and M. H. Bonds. 2021. "Effects of Changes in Temperature on Zika Dynamics and Control." *Journal of the Royal Society Interface* 18: 20210165.

Nguyen, K. H., P. H. Boersch-Supan, R. B. Hartman, S. Y. Mendiola, V. J. Harwood, D. J. Civitello, and J. R. Rohr. 2021. "Interventions Can Shift the Thermal Optimum for Parasitic Disease Transmission." *Proceedings of the National Academy of Sciences of the United States of America* 118: 2017537118.

Nova, N., E. R. Deyle, M. S. Shocket, A. J. MacDonald, M. L. Childs, M. Rypdal, G. Sugihara, and E. A. Mordecai. 2021. "Susceptible Host Availability Modulates Climate Effects on Dengue Dynamics." *Ecology Letters* 24: 415–425.

Nunn, C., and S. Altizer. 2006. *Infectious Diseases in Primates: Behavior, Ecology and Evolution*. Oxford, UK: Oxford University Press.

Ogden, N. H. 2017. "Climate Change and Vector-Borne Diseases of Public Health Significance." *FEMS Microbiology Letters* 364: fnx186.

Okuneye, K., and A. B. Gumel. 2017. "Analysis of a Temperature- and Rainfall-Dependent Model for Malaria Transmission Dynamics." *Mathematical Biosciences* 287: 72–92.

Paaijmans, K. P., S. Blanford, A. S. Bell, J. I. Blanford, A. F. Read, and M. B. Thomas. 2010. "Influence of Climate on Malaria Transmission Depends on Daily Temperature Variation." *Proceedings of the National Academy of Sciences of the United States of America* 107: 15135–39.

Paaijmans, K. P., A. F. Read, and M. B. Thomas. 2009. "Understanding the Link between Malaria Risk and Climate." *Proceedings of the National Academy of Sciences of the United States of America* 106: 13844–49.

Parham, P. E., and E. Michael. 2010. "Modeling the Effects of Weather and Climate Change on Malaria Transmission." *Environmental Health Perspectives* 118: 620–26.

Puntasecca, C. J., C. H. King, and A. D. LaBeaud. 2021. "Measuring the Global Burden of Chikungunya and Zika Viruses: A Systematic Review." *PLoS Neglected Tropical Diseases* 15: e0009055.

R Core Team. 2021. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing https://www.R-project.org/.

Read, N. R., J. R. Rooker, and J. P. Gathman. 1994. "Public Perception of Mosquito Annoyance Measured by a Survey and Simultaneous Mosquito Sampling." *Journal of the American Mosquito Control Association* 10: 79–87.

Reid, J. N., T. S. Hoffmeister, A. G. Hoi, and B. D. Roitberg. 2014. "Bite or Flight: The Response of Mosquitoes to Disturbance while Feeding on a Defensive Host." *Entomologia Experimentalis et Applicata* 153: 240–45.

Reiner, R. C., Jr., T. A. Perkins, C. M. Barker, T. Niu, L. F. Chaves, A. M. Ellis, D. B. George, et al. 2013. "A Systematic Review of Mathematical Models of Mosquito-Borne Pathogen Transmission: 1970–2010." *Journal of the Royal Society Interface* 10: 20120921.

Reisen, W. K., R. P. Meyer, and M. M. Milby. 1986. "Overwintering Studies on *Culex tarsalis* (Diptera: Culicidae) in Kern County, California: Temporal Changes in Abundance and Reproductive Status with Comparative Observations on *C. quinquefasciatus* (Diptera: Culicidae)." *Annals of the Entomological Society of America* 79: 677–685.

Robert, M. A., R. C. Christofferson, P. D. Weber, and H. J. Wearing. 2019. "Temperature Impacts on Dengue Emergence in the United States: Investigating the Role of Seasonality and Climate Change." *Epidemics* 28: 100344.

Rogers, D. J., J. E. Suk, and J. C. Semenza. 2014. "Using Global Maps to Predict the Risk of Dengue in Europe." *Acta Tropica* 129: 1–14.

Rohr, J. R., and J. M. Cohen. 2020. "Understanding how Temperature Shifts Could Impact Infectious Disease." *PLoS Biology* 18: e3000938.

Romeo-Aznar, V., R. Paul, O. Telle, and M. Pascual. 2018. "Mosquito-Borne Transmission in Urban Landscapes: The Missing Link between Vector Abundance and Human Density." *Proceedings Biological Sciences/The Royal Society* 285: 0826.

Rondón, S., C. León, A. Link, and C. González. 2019. "Prevalence of *Plasmodium* Parasites in Non-human Primates and Mosquitoes in Areas with Different Degrees of Fragmentation in Colombia." *Malaria Journal* 18: 276.

Rueda, L. M., K. J. Patel, R. C. Axtell, and R. E. Stinner. 1990. "Temperature-Dependent Development and Survival Rates of *Culex quinquefasciatus* and *Aedes aegypti* (Diptera: Culicidae)." *Journal of Medical Entomology* 27: 892–98.

Ruybal, J. E., L. D. Kramer, and A. M. Kilpatrick. 2016. "Geographic Variation in the Response of *Culex pipiens* Life History Traits to Temperature." *Parasites & Vectors* 9: 116.

Ryan, S. J., C. J. Carlson, E. A. Mordecai, and L. R. Johnson. 2019. "Global Expansion and Redistribution of *Aedes*-Borne Virus Transmission Risk with Climate Change." *PLoS Neglected Tropical Diseases* 13: e0007213.

Ryan, S. J., C. A. Lippi, and F. Zermoglio. 2020. "Shifting Transmission Risk for Malaria in Africa with Climate Change: A Framework for Planning and Intervention." *Malaria Journal* 19: 170.

Samson, D. R., L. A. Louden, K. Gerstner, S. Wylie, B. Lake, B. J. White, C. L. Nunn, and K. D. Hunt. 2019. "Chimpanzee (*Pan troglodytes schweinfurthii*) Group Sleep and Pathogen-Vector Avoidance: Experimental Support for the Encounter-Dilution Effect." *International Journal of Primatology* 40: 647–659.

Scott, T. W., and W. Takken. 2012. "Feeding Strategies of Anthropophilic Mosquitoes Result in Increased Risk of Pathogen Transmission." *Trends in Parasitology* 28: 114–121.

Shapiro, L. L. M., C. C. Murdock, G. R. Jacobs, R. J. Thomas, and M. B. Thomas. 2016. "Larval Food Quantity Affects the Capacity of Adult Mosquitoes to Transmit Human Malaria." *Proceedings Biological Sciences/The Royal Society* 283: 0298.

Shapiro, L. L. M., S. A. Whitehead, and M. B. Thomas. 2017. "Quantifying the Effects of Temperature on Mosquito and Parasite Traits that Determine the Transmission Potential of Human Malaria." *PLoS Biology* 15: e2003489.

Shocket, M. S., S. J. Ryan, and E. A. Mordecai. 2018. "Temperature Explains Broad Patterns of Ross River Virus Transmission." *eLife* 7: 37762.

Shocket, M. S., A. B. Verwillow, M. G. Numazu, H. Slamani, J. M. Cohen, F. El Moustaid, J. Rohr, L. R. Johnson, and E. A.

Mordecai. 2020. “Transmission of West Nile and Five Other Temperate Mosquito-Borne Viruses Peaks at Temperatures between 23°C and 26°C.” *eLife* 9: 58511.

Silver, J. B. 2008a. “Blood-Feeding and its Epidemiological Significance.” In *Mosquito Ecology: Field Sampling Methods*, edited by J. B. Silver, 677–769. Dordrecht: Springer.

Silver, J. B. 2008b. “Estimating the Size of the Adult Population.” In *Mosquito Ecology: Field Sampling Methods*, edited by J. B. Silver, 1273–1376. Dordrecht: Springer.

Smith, D. L., K. E. Battle, S. I. Hay, C. M. Barker, T. W. Scott, and F. E. McKenzie. 2012. “Ross, Macdonald, and a Theory for the Dynamics and Control of Mosquito-Transmitted Pathogens.” *PLoS Pathogens* 8: e1002588.

Smith, D. L., T. A. Perkins, R. C. Reiner, Jr., C. M. Barker, T. Niu, L. F. Chaves, A. M. Ellis, et al. 2014. “Recasting the Theory of Mosquito-Borne Pathogen Transmission Dynamics and Control.” *Transactions of The Royal Society of Tropical Medicine and Hygiene* 108: 185–197.

Sternberg, E. D., and M. B. Thomas. 2014. “Local Adaptation to Temperature and the Implications for Vector-Borne Diseases.” *Trends in Parasitology* 30: 115–122.

Styer, L. M., K. A. Kent, R. G. Albright, C. J. Bennett, L. D. Kramer, and K. A. Bernard. 2007. “Mosquitoes Inoculate High Doses of West Nile Virus as they Probe and Feed on Live Hosts.” *PLoS Pathogens* 3: 1262–70.

Tesla, B., L. R. Demakovsky, E. A. Mordecai, S. J. Ryan, M. H. Bonds, C. N. Ngonghala, M. A. Brindley, and C. C. Murdock. 2018. “Temperature Drives Zika Virus Transmission: Evidence from Empirical and Mathematical Models.” *Proceedings Biological Sciences/The Royal Society* 285: 20180795.

Thongsripong, P., J. M. Hyman, D. D. Kapan, and S. N. Bennett. 2021. “Human-Mosquito Contact: A Missing Link in our Understanding of Mosquito-Borne Disease Transmission Dynamics.” *Annals of the Entomological Society of America* 114: 397–414.

Turell, M. J., R. F. Tammariello, and A. Spielman. 1995. “Nonvascular Delivery of St. Louis Encephalitis and Venezuelan Equine Encephalitis Viruses by Infected Mosquitoes (Diptera: Culicidae) Feeding on a Vertebrate Host.” *Journal of Medical Entomology* 32: 563–68.

Valentine, M. J., C. C. Murdock, and P. J. Kelly. 2019. “Sylvatic Cycles of Arboviruses in Non-human Primates.” *Parasites & Vectors* 12: 463.

van den Driessche, P., and J. Watmough. 2002. “Reproduction Numbers and Sub-Threshold Endemic Equilibria for Compartmental Models of Disease Transmission.” *Mathematical Biosciences* 180: 29–48.

Villena, O. C., S. J. Ryan, C. C. Murdock, and L. R. Johnson. 2020. “Temperature Impacts the Transmission of Malaria Parasites by *Anopheles gambiae* and *Anopheles stephensi* Mosquitoes.” https://doi.org/10.1101/2020.07.08.194472.

Villena, O. C., S. J. Ryan, C. C. Murdock, and L. R. Johnson. 2022. “Temperature Impacts the Environmental Suitability for Malaria Transmission by *Anopheles gambiae* and *Anopheles stephensi*.” *Ecology* 103: e3685.

Walker, E. D., and J. D. Edman. 1985. “The Influence of Host Defensive Behavior on Mosquito (Diptera: Culicidae) Biting Persistence.” *Journal of Medical Entomology* 22: 370–72.

Walker, E. D., and J. D. Edman. 1986. “Influence of Defensive Behavior of Eastern Chipmunks and Gray Squirrels (Rodentia: Sciuridae) on Feeding Success of *Aedes triseriatus* (Diptera: Culicidae).” *Journal of Medical Entomology* 23: 1–10.

Wang, W., and X.-Q. Zhao. 2008. “Threshold Dynamics for Compartmental Epidemic Models in Periodic Environments.” *Journal of Dynamics and Differential Equations* 20: 699–717.

Wolfe, N. D., C. P. Dunavan, and J. Diamond. 2007. “Origins of Major Human Infectious Diseases.” *Nature* 447: 279–283.

Wonham, M. J., M. A. Lewis, J. Rencławowicz, and P. van den Driessche. 2006. “Transmission Assumptions Generate Conflicting Predictions in Host-Vector Disease Models: A Case Study in West Nile Virus.” *Ecology Letters* 9: 706–725.

Yan, J., L. Gangoso, S. Ruiz, R. Soriguer, J. Figuerola, and J. Martínez-de la Puente. 2021. “Understanding Host Utilization by Mosquitoes: Determinants, Challenges and Future Directions.” *Biological Reviews of the Cambridge Philosophical Society* 96: 1367–85.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Dahlin, Kyle J.-M., Suzanne M. O’Regan, Barbara A. Han, John Paul Schmidt, and John M. Drake. 2024. “Impacts of Host Availability and Temperature on Mosquito-Borne Parasite Transmission.” *Ecological Monographs* 94(2): e1603. https://doi.org/10.1002/ecm.1603